APEX-244

FC

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UNITED STATES ATOMIC ENERGY COMMISSION

SOME THERMAL PROPERTIES OF SOLID MATERIALS. PART I. METALS

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September 9, 1955

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SOME THERMAL PROPERTIES OF SOLID MATERIALS. PART I. METALS

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Thermodynamic Analysis

September 9, 1955

GEDR #102

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ABSTRACT

This report presents a review of the theoretical background of some thermal properties of metals and the results of a literature search for experimental data concerning various physical properties. Data is presented for thermal conductivity, specific heat, density, emissivity, melting points and thermal expansion coefficients, with emphasis on the first two of these items. Metals considered include aluminum, beryllium, inconel X, iron and steel, lead, molybdenum, niobium, and uranium.

SOME THERMAL PROPERTIES OF SOLID MATERIALS: PART I METALS

I. PREFACE

This study was undertaken in order to provide a suitable source file of thermal property data applicable to evaluation of heat storage and transmission characteristics of various materials. This report, the first of a series, deals exclusively with metallic materials encountered in Project work. Subsequent reports will deal with insulations, ceramics and miscellaneous materials. The properties considered, namely specific heat, thermal conductivity and density are those usually required for evaluation of steady state or transient temperature levels and gradients in heated structural materials. Some attention is also devoted to tabulations of coefficients of expansion and radiation emissivities since these values are of concern in many heating problems. Study of emissivities is somewhat cursory since a prior summary report is available.[1] Expansion data is not considered in great detail since most such information is readily available in standard references. The reference material cited in the text of this report represents only a small portion of data actually reviewed. A more complete reference file is maintained by the Thermodynamic Analysis Section.

The bulk of data found for zirconium is either classified or in process of review. These values were not included in this report section since an unclassified compilation was desirable. This report section is issued in loose leaf form since it is planned to issue additions and corrections as required.

1. See references at the end of the section.

The following paragraphs present the scope, manner of treatment and introductory material pertinent to the various items considered.

II. INTRODUCTION

A. Thermal Conductivity

1. General

From an engineering standpoint the most important point of concern in thermal conductivity usage is recognition of probable inaccuracies and limitations of application of available data. Consideration of subsequent source material suggests that tabulated thermal conductivity values should be accepted as applicable only if a reasonable margin of safety is indicated in caluclations. If a design is critically dependent on the value of thermal conductivity either a more detailed analysis of available data or recourse to experimental evaluation is required.

An examination of literature assembled for this report indicated that the uncertainties noted in thermal conductivity data are attributable to the following causes:

a) Conductivities of many materials are extremely sensitive to items such as physical constitution, minor changes of chemical composition and test environment.

b) Precise thermal conductivity measurements are difficult to obtain, particularly at elevated temperatures. It is not possible to standardize testing methods for all materials and temperature ranges.

c) Occasional erroneous data have become "standardized" as a result of repetition in standard handbooks and reference tests.

d) Large quantities of data are not available.

Within the scope of this report it is not possible to define "best" conductivity values for all cases, since adequate information is not available. The report attempts to present data applicable to most common engineering problems, with sufficient sources to permit the user to make an estimate of expected range of error, property variations with constitution, special conditions, etc.

2. Theory

A convenient means of highlighting the various facets of thermal conductivity work is the simplified theoretical discussion presented in the following paragraphs.

As an introductory simplified approach it can be assumed that conductivity, which, in part, represents the rate of diffusion of energy from molecule to molecule, increases with both "cohesive" forces between molecules and volumetric concentration of molecules in a substance. Thus, it would be expected that conductivity would decrease as a substance goes from solid to liquid to gas (i.e. from high to low molecular cohesion and concentration). Thus general behavior is illustrated in Fig. 1, a spectrum chart of thermal conductivities which serves as the frame of reference for this discussion. A particular example of such behavior is the system

ice-water-steam. Examination of typical spectrum values for solid and liquid metals also indicates that the "cohesive" forces in solids exert a significant conductivity effect. The "cohesive" forces apparently consist of two components. One component which promotes conduction results from the crystal structure of most metallic materials. Specifically, conduction is increased by a vibratory motion of the crystal lattice as a whole. The vibrations, or thermo-elastic waves, have been observed by X-ray diffraction techniques. The second conductivity effect relates to the electronic structure of the atom itself. The outermost electrons of a metallic atom (i.e. valence electrons) are not held as tightly in the atom structure as are innermost electrons. In the formation of a metal crystal the loosely held valence electrons become detached and free to move within the array of positive ions which constitute the remainder of the atoms. A metal crystal may be viewed as an orderly array of positive ions surrounded by clouds of electrons free to move within the metal structure. At uniform temperature conditions the electron movement is entirely random with no net migration of electrons. When a temperature difference exists within the metal there is a general drift tendency of electrons in the direction of temperature drop which results in a flow of energy. This effect is largely responsible for the high conductivity noted in metals. Substantiation of this theory can be gained by comparison of conductivities of metals and non-metallic solids shown in the spectrum chart. In the crystals of the non-metallic compounds valence electrons are transferred or shared between atoms to form the chemical bonds of the molecule. Thus the electrons are confined and drift does not occur. As a result non-metallic compounds generally have lower conductivities than metals.

The final point discussed in terms of the spectrum chart concerns materials whose conductivity is determined primarily by physical constitution rather than intrinsic atomic, molecular or crystal lattice characteristics. Mixing of compounds, which is typical of building and insulating materials creates marked differences of conductivity values. As an example most commercial items made from ceramics noted in the "pure non-metallic solids" band will have considerably lower thermal conductivities because of porosity effects. Specifically, the conductivity of a porous material is usually a composite of conductivity of the base material and air in the pores. Since air conductivity is low the net conductivity is considerably decreased. Most insulators, in fact, owe their low conductivity to their ability to hold air entrapped rather than inherent low conductivity of the base material. In many cases the conductivity of porous insulators is also affected and/or determined by internal radiation effects.

3. Types of Problems in Application

The brief discussion of theoretical aspects previously presented can be used to establish guides to some of the practical problems associated with use and evaluation of conductivity data. Metal conductivity is in part a function of crystal lattice structure and electron drift effects which are influenced by imperfections of overall lattice structure (the more uniform the lattice the lower the resistance to drift). Hence it could be anticipated that common metal variants including heat treatment, stress and deformation, trace impurities etc., which affect lattice characteristics, will also affect thermal conductivity. A listing and discussion of the effect of more common items follows.

4. Factors Affecting Thermal Conductivity of Metallic Materials

The following items refer to factors which can be expected to influence the thermal conductivity of metallic materials of specified nominal compositions.

a) Trace Impurities: Trace impurities tend to distort lattice structure and reduce thermal conductivity. Thus, some degree of variation of conductivity could be expected for most commerical materials since the values for alloying elements and trace impurities are usually specified in a range rather than as a unique value. In general this effect is of negligible importance except for pure metals. (i.e. an alloy which already has a disturbed lattice should be less affected by impurities than should a pure metal which has a more perfect lattice).

b) Pressure, Stress, Deformation Effects: Stress and deformation could be expected to decrease conductivity because of the introduction of lattice distortion. However, on the basis of limited data available* it appears that these effects are of negligible significance. An exception may be cold-work effects in anisotropic metals. Similarly hydrostatic pressure exerts a slight effect on thermal conductivity of metals but the effect is so small as to be of essentially academic interest.*

* Work of P. W. Bridgman quoted in Austin. J. B., "The Flow of Heat in Metals" (Ref. 3).

c) Grain Size, Directional Effects: Metals which do not crystallize in the cubic system sometimes exhibit anisotropic conductivity effects. Thus, materials such as tin, zinc, zirconium and other non-cubic systems may in some cases exhibit conductivities which vary with direction of heat flow through the specimen. The direct effect of anisotropic structure is usually considered as a function of grain size and orientation. Specifically, the conductivity of of cubic system materials such as copper, aluminum and most steels is virtually independent of grain size. For an anisotropic metal, however, the variation with grain size and orientation may be of some concern. It could be anticipated for example that the conductivity of hexagonal system materials such as titanium and zirconium would vary with grain size and also with previous working history, since metal working methods for these materials yield preferred orientations. Beryllium might also be expected to show anisotropic behavior but this does not appear to be of much concern since reactor grade material is made by powder metallurgy techniques. This yields small particle size and adequate random structure so as to eliminate anisotropic effects.

d) Phase Changes and Transformations: Many materials undergo changes of crystal structure, transformations (i.e. martensite-pearlite-ferrite in iron and steels) changes of order etc, under various conditions of time at temperature. In general all of these effects can be expected to influence conductivity to some extent. Since many types of variation are possible discussion is presented, where possible, in terms of specific materials in subsequent sections.

5. Nuclear Irradiation Effects

Although few data are available with regard to nuclear irradiation effects, some insight into the general problems which could be anticipated is provided by the preceding theoretical discussion. Nuclear irradiation tends to alter crystal lattice structure. In metals the major conductivity contributant is electron drift which is essentially unaffected by irradiation. Thus, it would not be expected that metal characteristics would change greatly under nuclear irradiation. In the non-metallic solids, where lattice vibration is a major contributant to thermal conductivity, mild to severe conductivity decreases could be anticipated to result from irradiation. It would also be expected that the more orderly* a system the more severe the decrease in conductivity. Marked changes of conductivity of graphite and beryllia under irradiation have been recorded. Also of significance is the relation of temperature to irradiation damage. In general, the degree of decrease in thermal conductivity should decrease with increasing temperature since increased temperature anneals out radiation-caused structural alterations.

6. Estimating Methods

Since thermal conductivity literature data for some materials is not extensive, a need for an estimating method for unmeasured materials

* e.g. In the sense that an annealed material is usually more "orderly" than a quenched material, a pure metal crystal is more "orderly" than an alloy metal.

is apparent. Becuase of the complexity of the conductivity phenomena no simple, reliable method exists; however, certain rough approximations and guides are available.

The most important estimating device is based on the analogy between thermal and electrical conductivity which can be predicted from theoretical considerations. The relation, known as the Weidemann-Franz-Lorenz equation is:

$$L = \frac{K}{K_e T}$$

where:

K	=	thermal conductivity	watt/cm - ^{o}K
K_e	=	electrical conductivity	$(ohm\text{-}cm)^{-1}$
T	=	absolute temperature	^{o}K
L	=	the "Lorenz" number	$(volt/^{o}K)^{2}$

Considerable experimental evidence indicates that a good approximation of the variation of thermal conductivity with temperature can be obtained from knowledge of a low temperature conductivity value and the measured variation of electrical conductivity with temperature. This is of extreme value since electrical conductivity is easily measurable. In the usual case a closer correlation of data is obtained by a relation of the form

$$K = L' K_e T + B$$

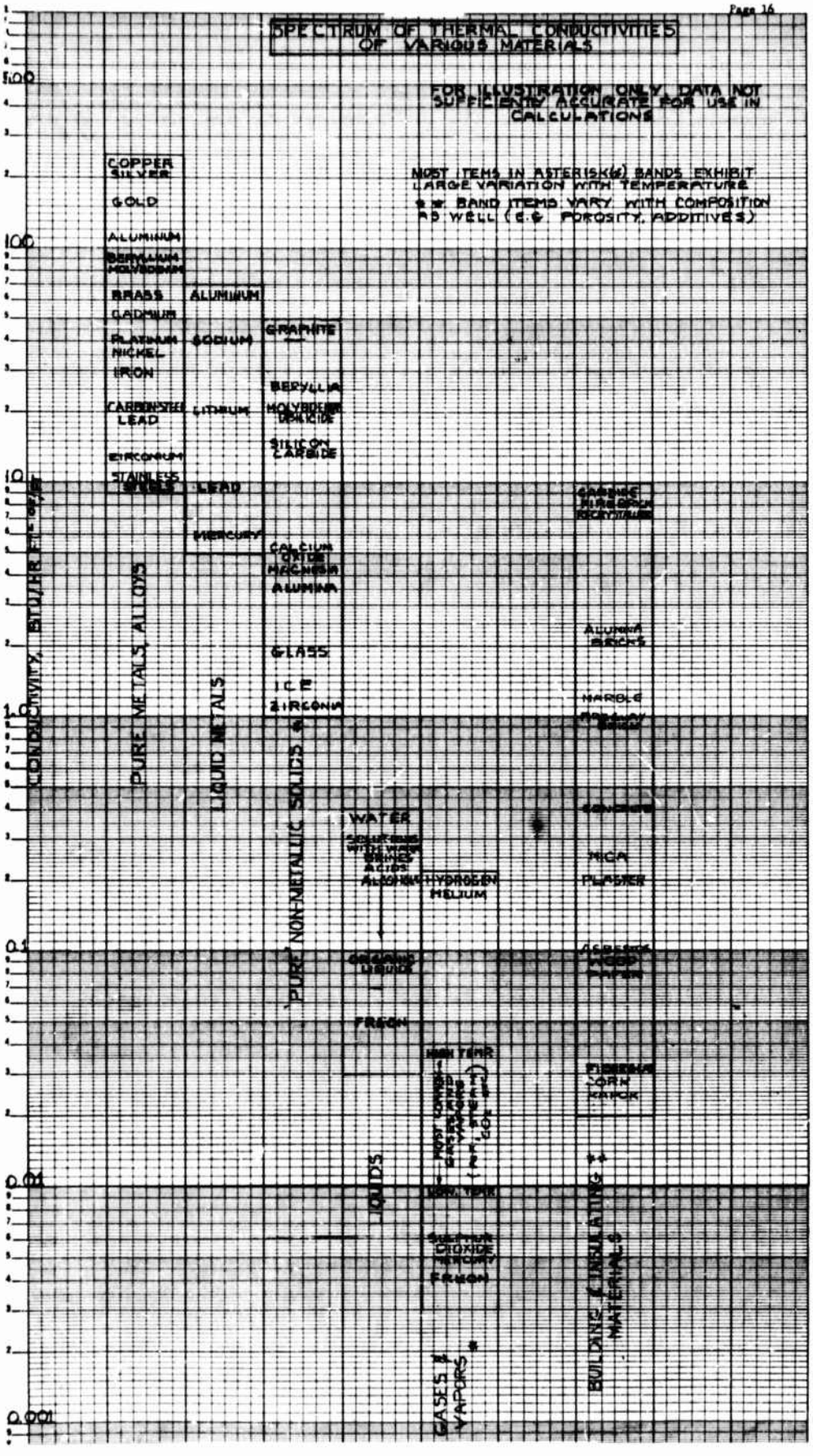
wherein L' and B are constants. In this equation B accounts for

lattice conduction, an item which is not of concern to the transmission of electric current.

A second use of the Lorenz type equations concerns the relative constancy of the Lorenz number L for pure metals. For the units shown the value of L for most pure metals is in the range of $22 - 30 \times 10^{-9}$. This relationship may be used to obtain a rough initial estimate of thermal conductivity of pure metals from electrical measurements.

The Lorenz type relation is also applicable to various alloys and/or families of alloys. In this case, however, no unique constant is apparent, so the relationship is only of interest in predicting variation of conductivity with temperature having once defined base values and electrical conductivity.

Another estimating, or more properly an extrapolation technique, applicable to families of alloys can be derived from examination of typical conductivity data. Essentially all conductivity data for both low and high alloy steels converges at approximately $1700^{\circ}F$. If a room temperature conductivity value for a particular steel is available a reasonable extrapolation of data is obtained by assuming linear variation between the room temperature value and the point of convergence. A similar convergence temperature can be found for copper alloy systems and probably others as well.


SPECTRUM OF THERMAL CONDUCTIVITIES OF VARIOUS MATERIALS
FOR ILLUSTRATION ONLY DATA NOT SUFFICIENTLY ACCURATE FOR USE IN CALCULATIONS
MOST ITEMS IN ASTERISK(*) BANDS EXHIBIT LARGE VARIATION WITH TEMPERATURE
* BAND ITEMS VARY WITH COMPOSITION AS WELL (E.G. POROSITY, ADDITIVES)
CONDUCTIVITY, BTU/HR FT °F
500
100
10
1.0
0.1
0.01
PURE METALS, ALLOYS
COPPER
SILVER
GOLD
ALUMINUM
BERYLLIUM
MOLYBDENUM
BRASS
CADMIUM
PLATINUM
NICKEL
IRON
CARBON STEEL
LEAD
ZIRCONIUM
STAINLESS STEEL
LIQUID METALS
ALUMINUM
SODIUM
LITHIUM
LEAD
MERCURY
PURE NON-METALLIC SOLIDS *
GRAPHITE
BERYLLIA
MOLYBDENUM DISULFIDE
SILICON CARBIDE
CALCIUM OXIDE
MAGNESIA
ALUMINA
GLASS
ICE
ZIRCONIA
WATER
ALCOHOL
HYDROGEN
HELIUM
FREON
LIQUIDS
GASES & VAPORS *
BUILDING & INSULATING MATERIALS
GRANITE
ALUMINA BRICKS
MARBLE
CONCRETE
MICA
PLASTER
FIBERBOARD
CORK
BRICK

B. Specific Heat*

Specific heat, can usually be either measured or estimated within accuracy limits sufficient for almost all engineering applications. For all practical purposes specific heat may be considered to be an extensive property of a material which is independent of physical constitution. In this report no attempt was made nor was it necessary, to review all original specific heat references such as was done with thermal conductivity data. For the most part the extensive U. S. Bureau of Mines data compiled by Kelley was accepted as adequate representative data. Additional material was added to cover the literature years not considered in the Kelley reports in some cases.

In the absence of applicable data any of the following relationships can be used to estimate specific heat data.

1. The heat capacity of a heterogeneous mixture is a simple additive property. Most alloys can be assumed to behave as if they were simple mixtures of metallic elements. Hence the specific heat of an alloy can usually be determined by simple weighting of specific heat of component metals.

2. The specific heat of all materials is zero at zero absolute temperature.

* Ordinarily the terms specific heat and heat capacity are used interchangeably in engineering work. Actually, since specific heat is the ratio of the heat or thermal capacity of a material to the thermal capacity of water at 15°C (which is unity for all practical purposes), the numerical values of heat capacity and specific heat are the same. In this report the term specific heat is often used to represent what should technically be defined as heat capacity.

The major specific heat variation occurs between absolute zero and the range of 20-200°F for most metallic elements. Beyond this range the specific heat of most metallic elements having an atomic weight greater than 55 increases only slightly with temperature, and can be evaluated by the rule of Dulong and Petit:

$$\text{Specific Heat} \times \text{Atomic Weight} \cong 6.2$$

The first of the preceding relationships is considerably more reliable than the latter. No further discussion of metal specific heats is considered since data applicable to most problems is readily available.

REFERENCES

1. Arnaiz, J. B., "Normal Total Emissivity of Various Materials as Functions of Temperature and Surface". XDC 55-3-39 (1955) Uncl.

2. Wilson, A. H., "The Theory of Metals", Cambridge University Press 1936.

3. Austin, J. B., "The Flow of Heat in Metals", American Society for Metals 1942.

4. Jakob, M., "Heat Transfer", John Wiley and Sons., 1949.

5. Dobbins, J. P., "Evaluation of Thermal Properties of Metals, Survey of Method and Theory", NA-48-913.

6. Kowalczyk, L. S., "Thermal Conductivity and Its Variability With Temperature and Pressure", ASME Paper 54-A-90, 1954.

PROPERTIES OF METALS

D A T A S E C T I O N

ALUMINUM

Data pertinent to most physical properties of structural aluminum alloys are presented in considerable detail in manufacturer's catalogs, and are not reviewed herein. Approximate values for items not considered in detail are as follows:

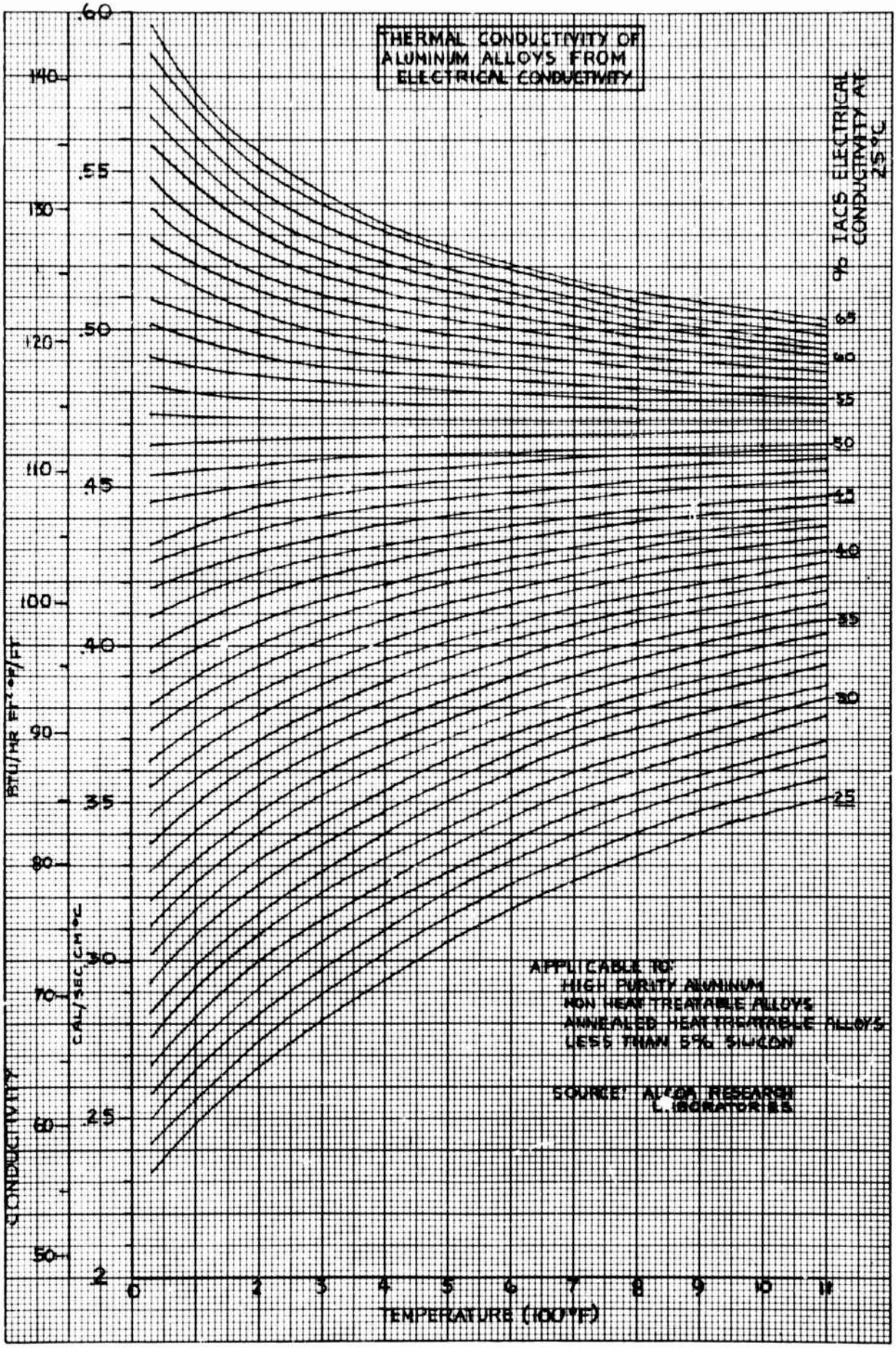
Density	0.098 - 0.104 lbs/in^3
Melting Range	1212°F (pure aluminum)
	950 - 1220°F most alloys
Boiling Point	5120°F
Coefficient of Thermal Expansion:	12-15x10^{-6} $\frac{\text{in}}{\text{in}}$ °F
	mean for 70-570°F
Molecular Weight	26.97

Thermal Conductivity

Although aluminum alloys are widely used in heating applications relatively little experimental information exists concerning thermal conductivity as a function of temperature. Data from various sources are shown in the following figures. In general, consistent conductivity data can only be obtained from tests of fully annealed alloy specimens. Data for various tempers at elevated temperatures are erratic because physical changes occur which alter conductivity. Such variations are shown in the works of Evans, Kempf, Bungardt and Kallenbach. (See references at end of section).

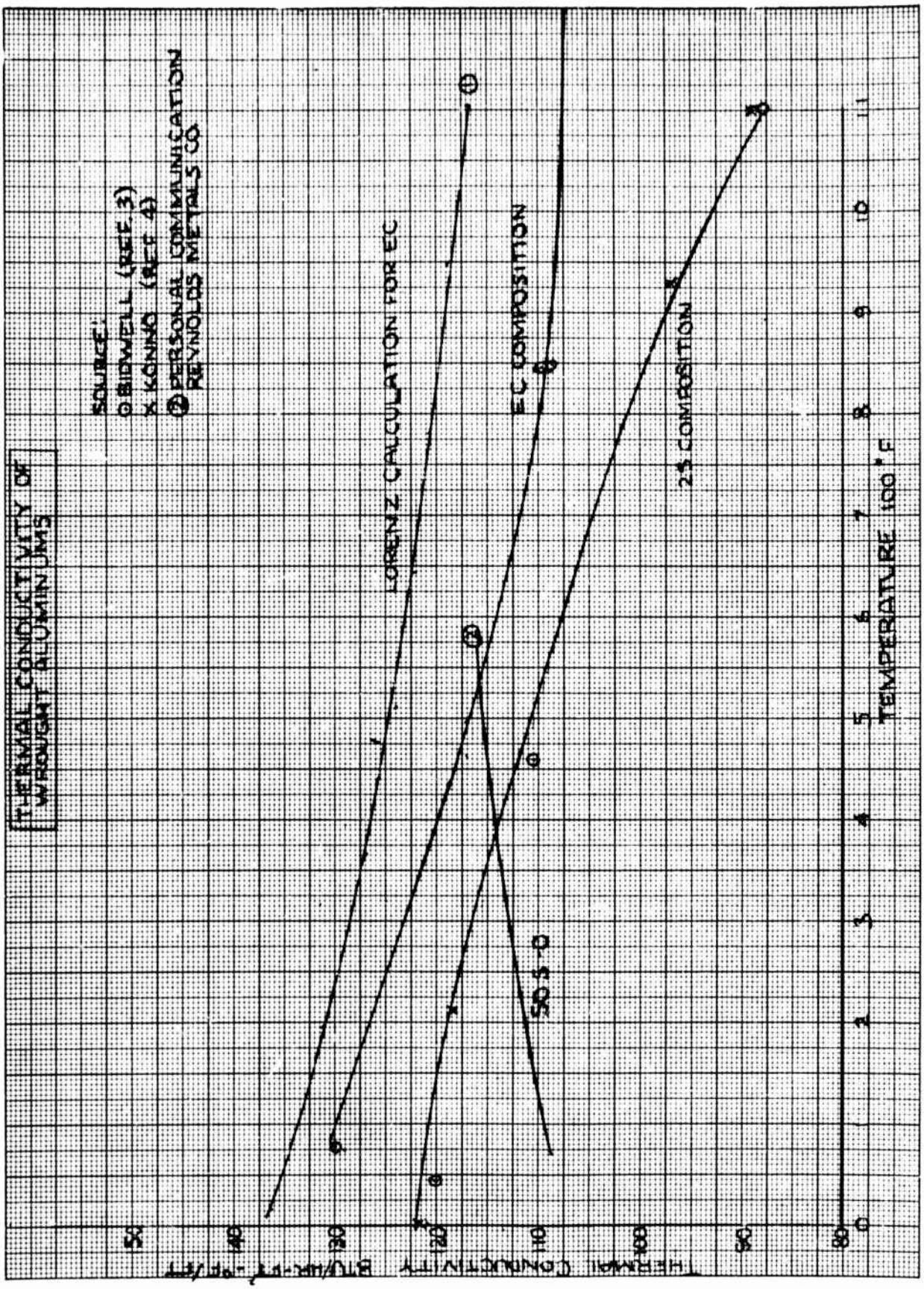
The conductivity of aluminum alloys usually decreases with increasing concentration of alloying element. Also, the conductivity of the annealed alloy is usually higher than that of any other temper. Conductivity is usually increased by

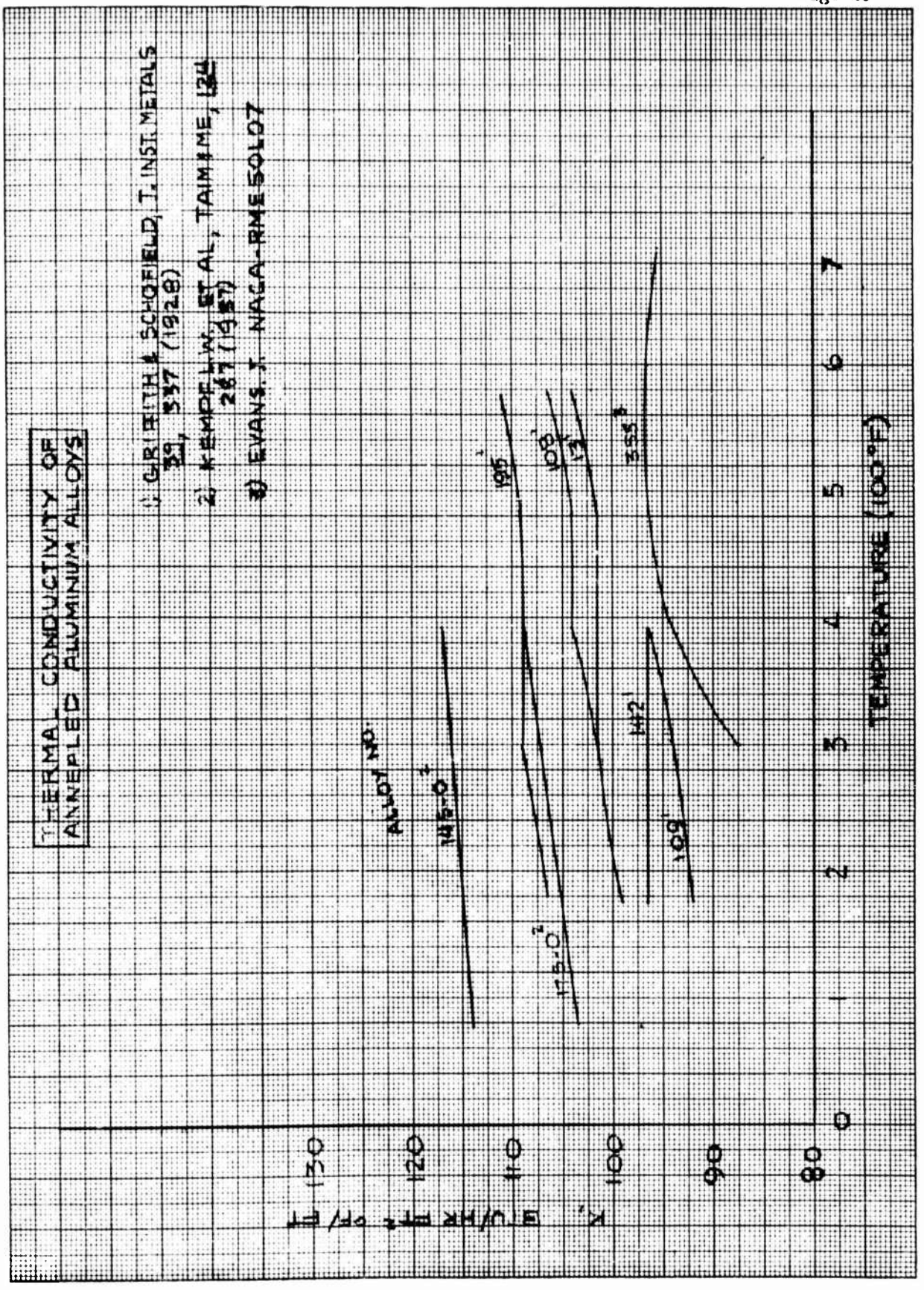
artificial aging and lowered by solution heat treatment. A convenient method of estimating thermal conductivity of various aluminum alloys is by analogy to electrical conductivity (Lorenz function) as illustrated on one of the graphs. The electrical conductivity required for this estimate is tabulated in most manufacturer's catalogs, and typical values are shown herein. Data for most important aluminum alloys fit this relation at room temperature to within 6%, except for alloys containing more than 5% silicon. Probable accuracy up to 600°F appears to be no better than 10%.

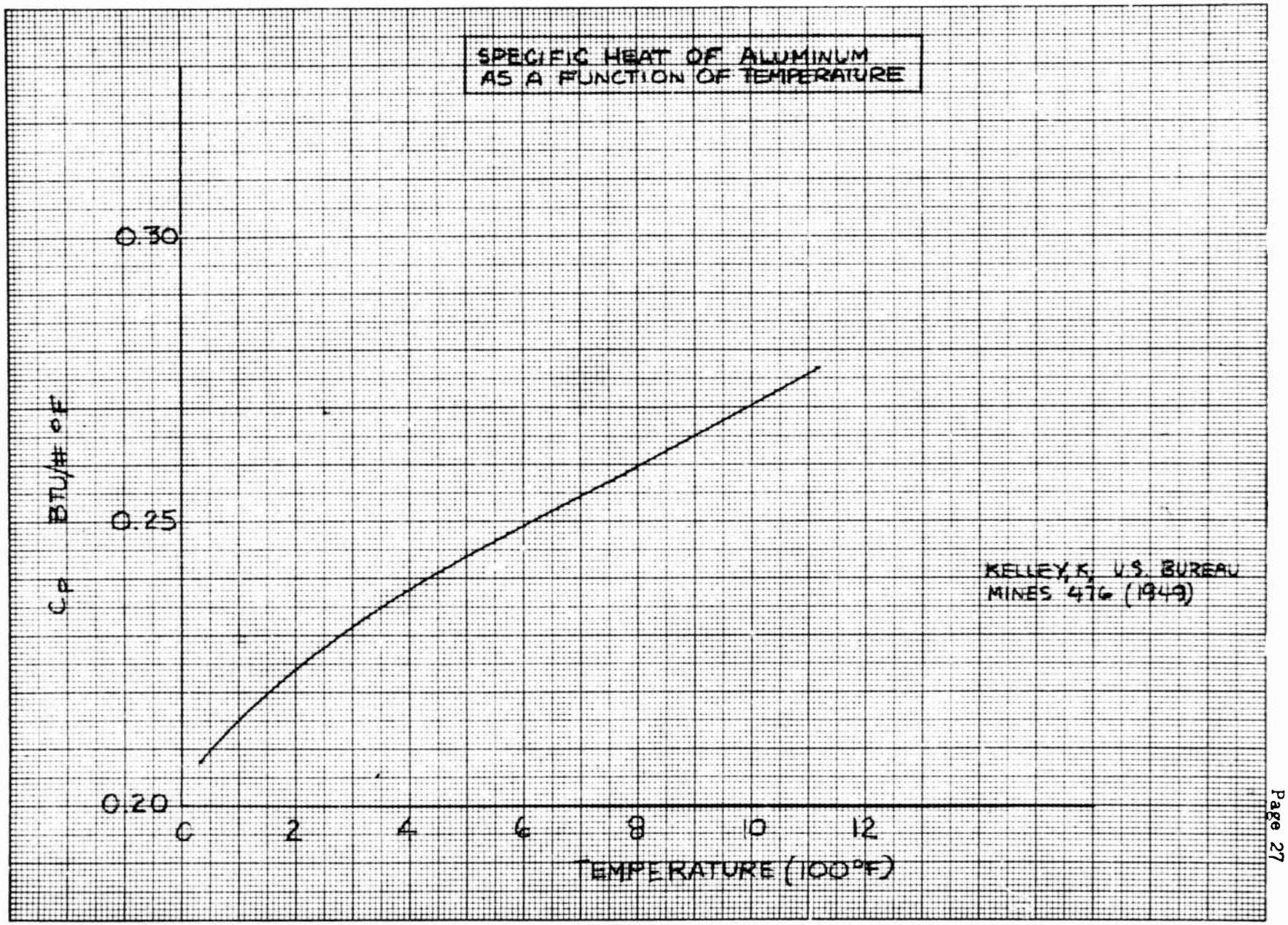

THERMAL CONDUCTIVITY OF ALUMINUM ALLOYS FROM ELECTRICAL CONDUCTIVITY
% IACS ELECTRICAL CONDUCTIVITY AT 25°C
BTU/HR FT²°F/FT
CAL/SEC.CM.°C
CONDUCTIVITY
TEMPERATURE (100°F)
APPLICABLE TO:
HIGH PURITY ALUMINUM
NON HEAT TREATABLE ALLOYS
ANNEALED HEAT TREATABLE ALLOYS
LESS THAN 5% SILICON
SOURCE: ALCOA RESEARCH LABORATORIES

ELECTRICAL CONDUCTIVITY OF ALUMINUM ALLOYS FOR USE IN EVALUATION OF THERMAL CONDUCTIVITY

Alloy and Temper	Electrical Conductivity % of International Annealed Copper Standard (% IACS)
EC-O	62
EC-H19	62
2S-O	59
2S-H18	57
3S-O	50
3S-H12	42
3S-H14	41
3S-H18	40
4S-O	42
4S-H38	42
11S-T3	40
14S-O	50
14S-T4	30
14S-T6	40
17S-O	45
17S-T4	30
A17S-T4	40
18S-O	50
18S-T61	40
B18S-O	50
B18S-T72	40
24S-O	50
24S-T3	30
25S-O	50
25S-T6	40
32S-O	40
32S-T6	35
50S-O	40
50S-H38	40
A51S-O	55
A51S-T6	45
52S-O	35
52S-H38	35
56S-O	29
56S-H38	27
61S-O	45
61S-T4	40
61S-T6	40
62S-O	45
62S-T4	40
62S-T6	40
63S-T42	50
63S-T5	55
63S-T6	55
75S-T6	30
R301-O	50
R301-T4	30
R301-T6	40


THERMAL CONDUCTIVITY OF WROUGHT ALUMINUMS
SOURCE:
① BIDWELL (REF. 3)
X KONNO (REF. 4)
② PERSONAL COMMUNICATION REYNOLDS METALS CO.
LORENZ CALCULATION FOR EC
EC COMPOSITION
2S COMPOSITION
50S-O
THERMAL CONDUCTIVITY BTU/HR-FT²-°F/FT
TEMPERATURE 100°F


THERMAL CONDUCTIVITY OF ANNEALED ALUMINUM ALLOYS
1) G.R. KEITH & SCHOFIELD, T. INST. METALS 29, 337 (1928)
2) KEMPF, L.W. ET AL., TAIME, 124 287 (1937)
3) EVANS, J. NACA-RME50L07
K, BTU/HR FT² °F/FT
TEMPERATURE (100°F)
ALLOY NO.
145-O
175-O
195
108
43
356
142
109


SPECIFIC HEAT OF ALUMINUM
AS A FUNCTION OF TEMPERATURE
0.30
0.25
0.20
C_p BTU/# °F
0
2
4
6
8
10
12
TEMPERATURE (100°F)
KELLEY, K., U.S. BUREAU
MINES 476 (1949)

REFERENCES

1. Kelley, K. K., "Contributions to the Data on Theoretical Metallurgy", U. S. Bureau of Mines Bulletin 476, 1949

2. Bungardt, W., and Kallenbach, R., "Zeitschrift für Metallkunde" 42 82-91 (1951).

3. Bidwell, C. C. and Hogan, C. L., "Thermal Conductivity of Aluminum: Solid and Liquid States", Jour. App. Physics 18 776 1947.

4. Konno, S., Phil. Mag. 40 542 (1920)

5. Evans, J., "Thermal Conductivity of 14 Metals and Alloys Up to 1100°F" NACA RM E50L07 1951.

6. Kempf, L. W., et. al., "Thermal and Electrical Conductivities of Aluminum Alloys" Trans. Am. Inst. Met and Min. Engrs., 124 285 1937.

7. Griffiths, E., Schofield, F. H., "The Thermal and Electrical Conductivities of some Aluminum Alloys and Bronzes", J. Inst. Metals, 39 337 (1928).

ADDENDUM

(Aluminum)

Additional Data from:

"Some Physical Properties of Aluminum at Elevated Temperatures"

Part I. Thermal Conductivity and Electrical Resistivity, Power, R. W. Hickman, M. J.

Part II. Linear Thermal Expansion, Barber, C. R.

Metallurgia (The British Journal of Metals) November 1949, pgs. 15-21.

THERMAL CONDUCTIVITY

The above reference presents thermal conductivities and electrical resistivities for a wide range of aluminum alloys (nine wrought and ten cast alloys), which had been specially heat treated at about 160°C. It was observed that heating above this temperature produced considerable changes in the thermal and electrical resistivities, but that sufficient heating at 572°F caused the changes to reach completion for most of the alloys. It was observed that this heat treatment resulted in appreciable increases in electrical conductivity (20 - 30% for several alloys). Conductivity and composition data too extensive to be included here are presented in this report. The work is summarized in the following equation, applicable from 20 - 300°C.

$$K = 0.53 \times 10^{-8} \frac{T}{\rho} + 0.02$$

where K = cal/cm^2-sec-°C/cm

ρ = ohms/cm^2/cm

T = °K

This equation correlates all data except that for alloys high (~11%) in silicon to within about 5%.

LINEAR THERMAL EXPANSION

It was observed that thermal expansion measurements could not be reproduced until the specimens had been stabilized by heat treatment at 572°F. The mean coefficients for a considerable number of heat treated cast and wrought alloys fell within the range 11-14x10^{-6} in/in-°F for temperatures 32-572°F.

INCONEL X

Thermal Conductivity

The values presented by the two investigators are in good agreement. Composition of the specimens is as follows:

	Ni	Cr	Fe	Remainder			
Ref. 1	73.2	14.4	7.0	Si	Mn	C	
Ref. 2	73.4	14.6	6.9	Ti	Cb	Al	C

Specific Heat

The specific heat is given (Ref. 3)

as

Temp. Range	Mean Specific Heat
68 - 212°F	0.10 - 0.11 BTU/lb - °F
68 - 1652°F	0.13

Miscellaneous Properties

The following data are from Ref. (3)

Density 0.30 lb/in^3 (Specific gravity 8.3)

Melting Range 2450 - 2600°F

Composition 70 Ni, 14-16 Cr. 5-9 Fe

plus small amounts of other metals.

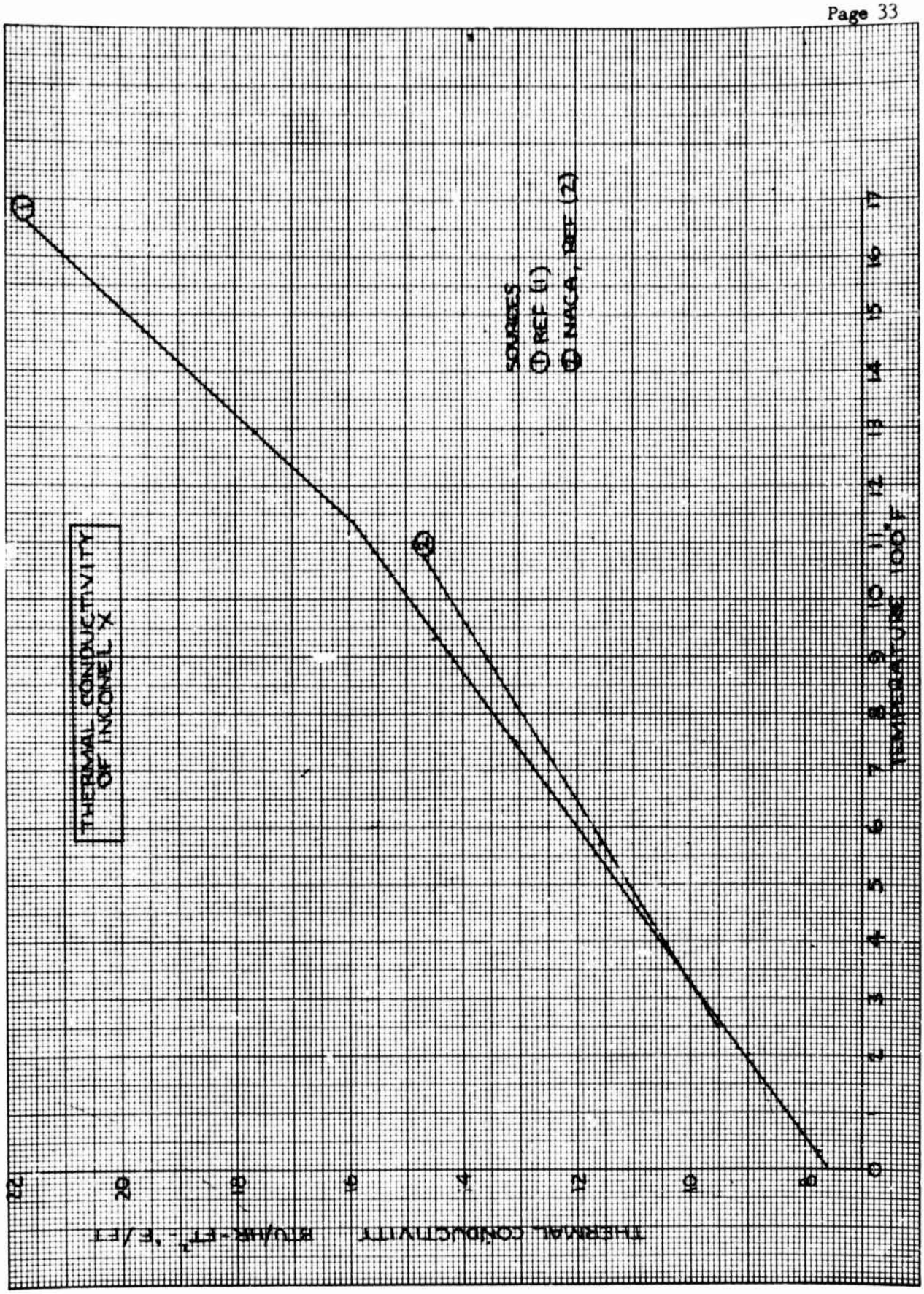
REFERENCES

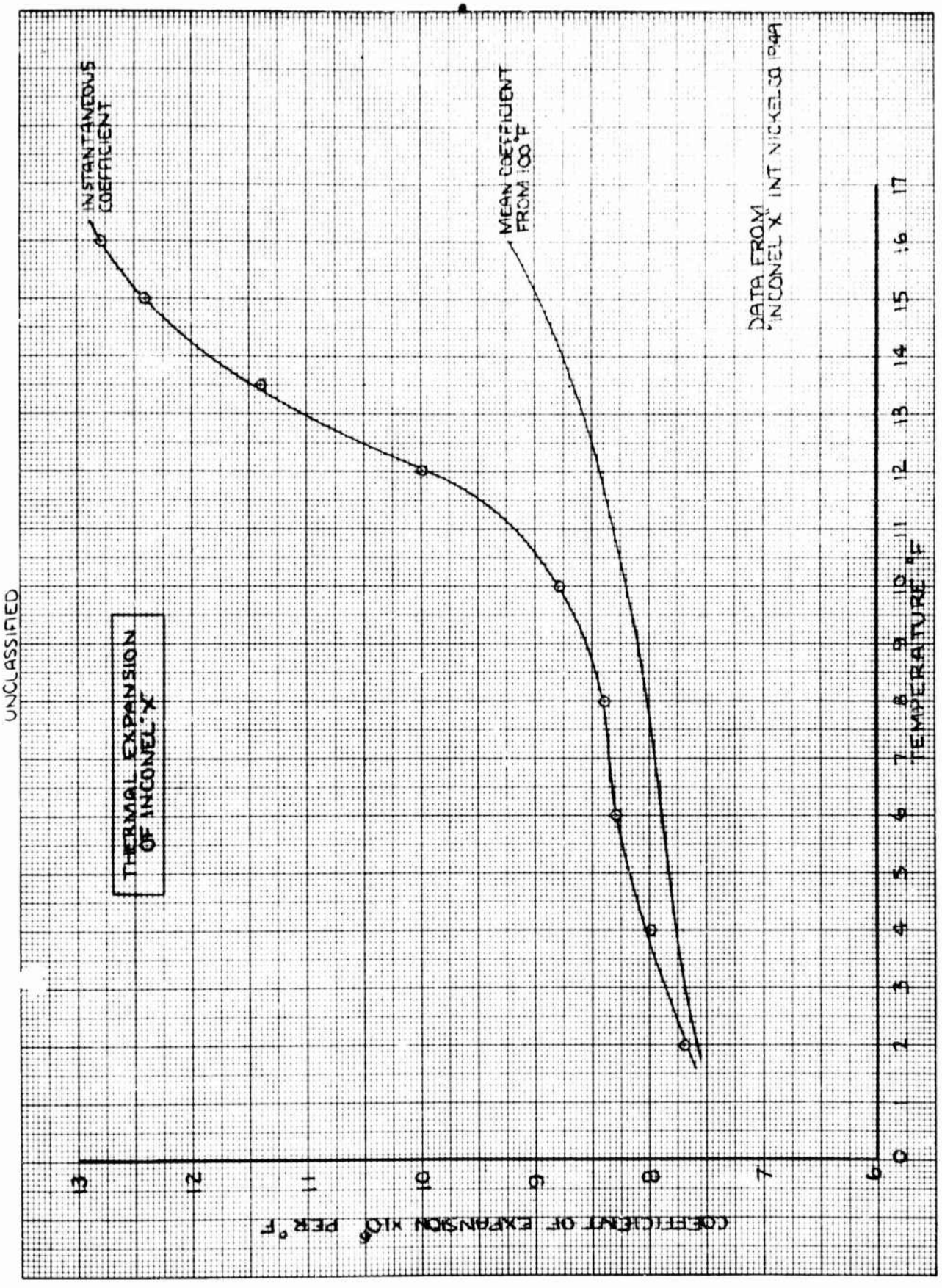
1. Hogan, C. L., and Sawyer, R. B., "The Thermal Conductivity of Metals at High Temperatures", Jour. App. Physics 23, 2, 177 (1952).

2. Evans, J. E., Jr., "Thermal Conductivity of 14 Metals and Alloys Up to 1100°F", NACA RM E 50L07 1951 (Uncl).

3. "Inconel X, Data and Information", Int. Nickel Co., 1949.

4. G. E. Design Data - Solid Properties.


THERMAL CONDUCTIVITY OF INCONEL X
SOURCES
① REF (1)
② NACA, REF (2)
TEMPERATURE, °F x 10⁻²
THERMAL CONDUCTIVITY BTU/HR-FT-°F/FT


UNCLASSIFIED
THERMAL EXPANSION OF INCONEL "X"
INSTANTANEOUS COEFFICIENT
MEAN COEFFICIENT FROM 100°F
DATA FROM "INCONEL "X" INT NICKEL CO 1949
COEFFICIENT OF EXPANSION x10⁶ PER °F
TEMPERATURE °F
6
7
8
9
10
11
12
13
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

BERYLLIUM

Data presented in this section are exclusively concerned with high density, high purity beryllium such as is usually employed in reactor work (99 + % pure). Detailed source material is available in reference 1.

Thermal Conductivity

The usual values quoted for high purity beryllium are based on the work of Grenell, et. al. quoted in reference 1. These data appear consistent with low temperature (32-200°F) values quoted in various secondary references and the work of Powell (7). Early data of Lewis (2) appears inconsistently high.

Specific Heat

Almost all of the specific heat data available prior to 1949 were reviewed and averaged by Kelley (3). Another important review of the literature was made by the NBS investigators (6). Both reviews point out questionable data (e.g. that of Losano). The NBS data (including both Brush QT and NBS BL Beryllium) are in good agreement with most of the original work reviewed by Kelley and therefore with the average line he presents.

Density

The variation of density with temperature illustrated is based on the work of Gordon (5). The indicated range is based on reported densities for various methods of producing high density beryllium.

Other Properties (ref. 1)

Melting Point	$\sim$	2400° ± 50°F
Boiling Point	$\sim$	5380°F
Emissivity	$\sim$	0.61
Molecular Weight		9.013

REFERENCES

1. Udy, M. C., et. al. "The Properties of Beryllium" AECD 3382 1949 (uncl.)

2. Lewis, E. J., "Some Thermal And Electrical Properties of Beryllium", Phys. Rev. 34 1575 (1929).

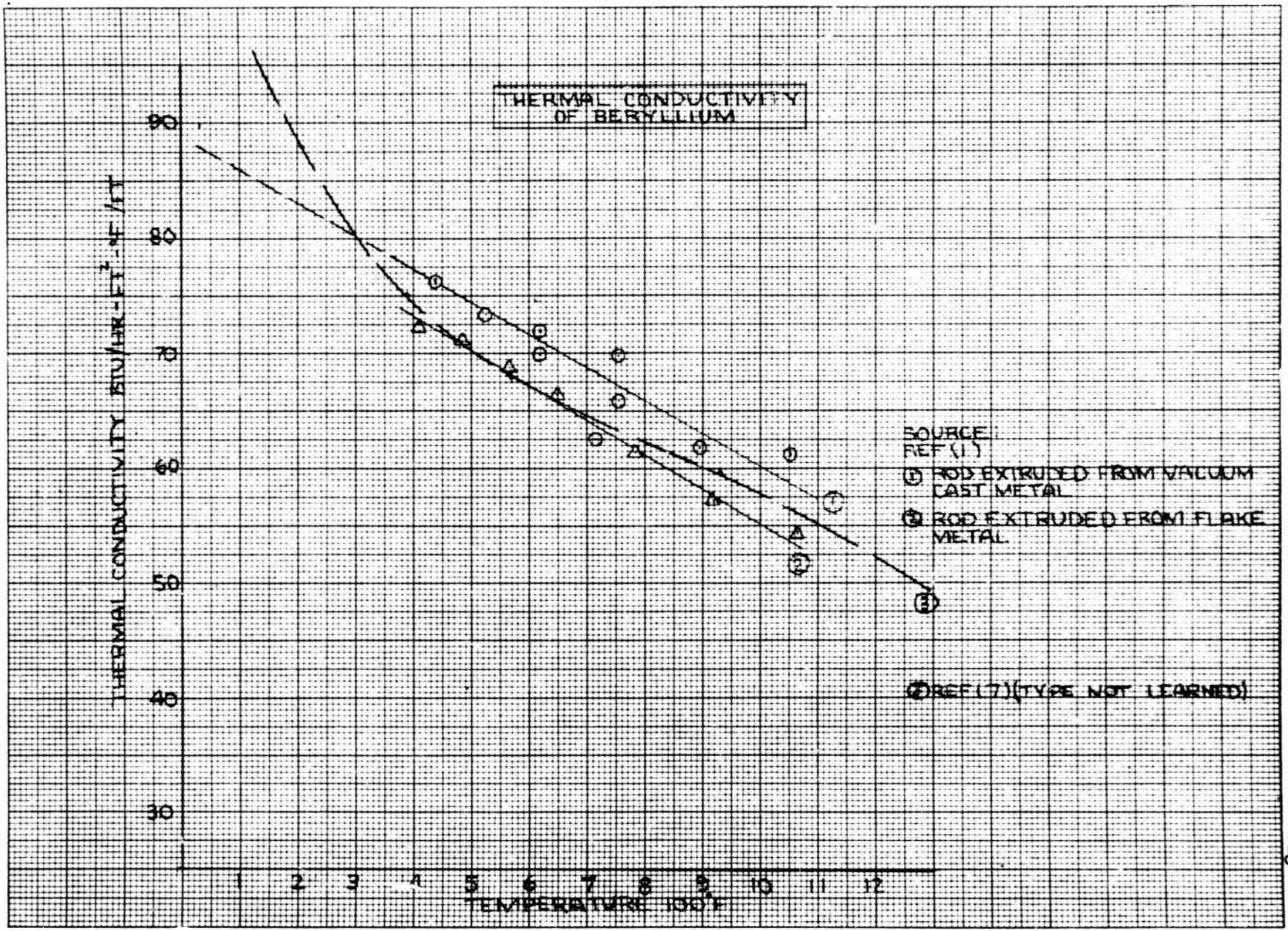
3. Kelley, K. K., "Contributions tc the Data on Theoretical Metallurgy", U. S. Bureau of Mines, Bulletin 476, 1949.

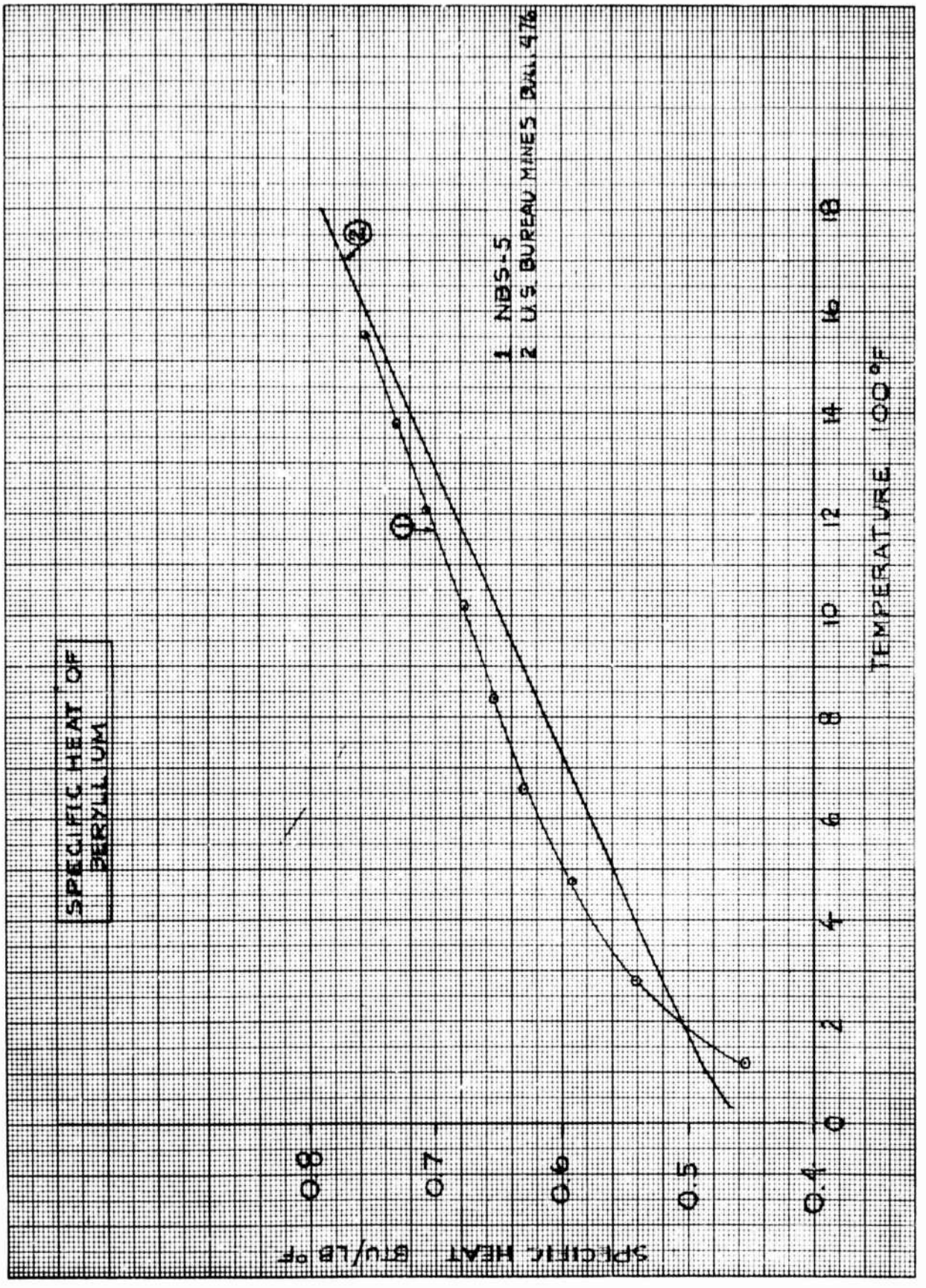
4. Losano, L., Allumino., 8, 67-75 1939.

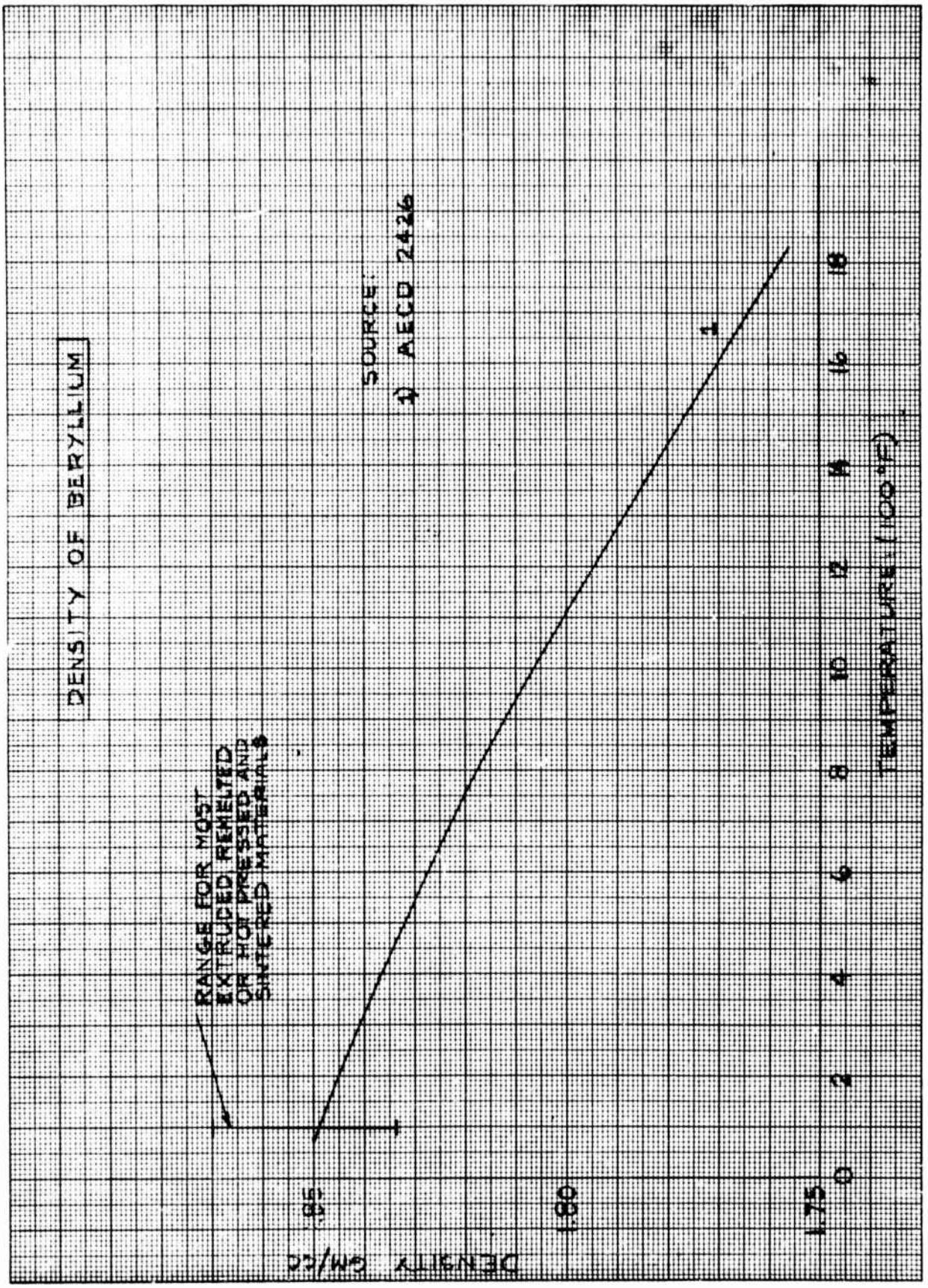
5. Gordon, P. "A High Temperature Precision X-ray Camera: Some Measurements of the Thermal Expansion of Beryllium", Uncl. AECD-2426 1948.

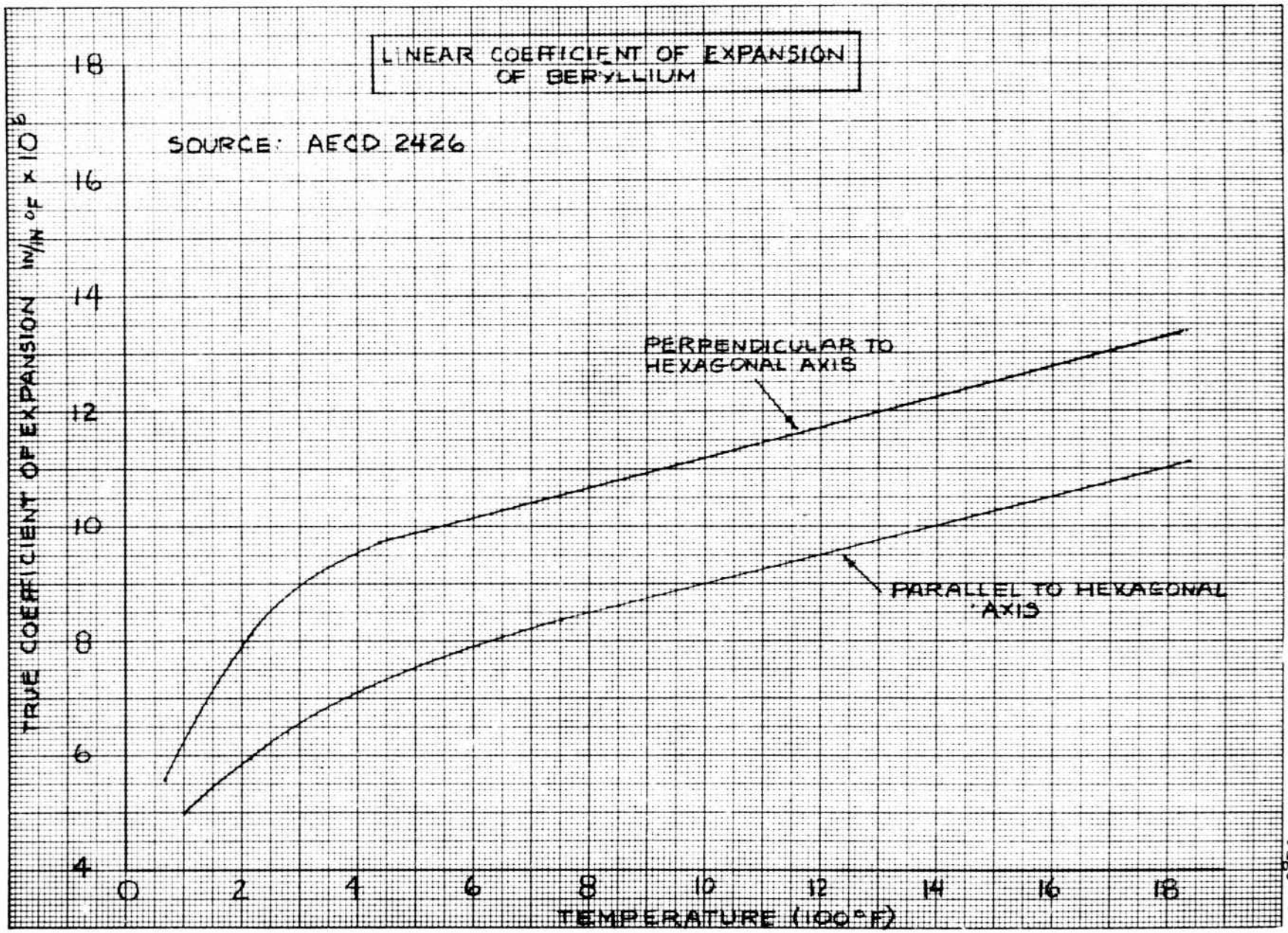
6. Ginnings, D. C., Douglas, T. B., Ball, A. F., "Specific Heat of Beryllium Between 0 and 900°C", NBS 5, AECD 2657.

7. Powell, R. W., Phil. Mag., 44 657, 1953.


THERMAL CONDUCTIVITY OF BERYLLIUM
THERMAL CONDUCTIVITY BTU/HR-FT-°F
90
80
70
60
50
40
30
1
2
3
4
5
6
7
8
9
10
11
12
TEMPERATURE 100°F
SOURCE
REF (1)
① ROD EXTRUDED FROM VACUUM CAST METAL
② ROD EXTRUDED FROM FLAKE METAL
③ REF (7) (TYPE NOT LEARNED)


SPECIFIC HEAT OF BERYLLIUM
1 NBS-5
2 U.S. BUREAU MINES
SPECIFIC HEAT BTU/LB °F
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
14
16
18
TEMPERATURE 100 °F


DENSITY OF BERYLLIUM
SOURCE:
1) AECD 2426
RANGE FOR MOST EXTRUDED REMELTED OR HOT PRESSED AND SINTERED MATERIALS
DENSITY GM/CC
1.80
1.75
TEMPERATURE (100 °F)
0
2
4
6
8
10
12
14
16
18
1


LINEAR COEFFICIENT OF EXPANSION OF BERYLLIUM
SOURCE: AECD 2426
TRUE COEFFICIENT OF EXPANSION IN/IN °F x 10⁶
18
16
14
12
10
8
6
4
0
2
4
6
8
10
12
14
16
18
TEMPERATURE (100°F)
PERPENDICULAR TO HEXAGONAL AXIS
PARALLEL TO HEXAGONAL AXIS

IRON AND STEEL

No attempt is made to define detailed characteristics of various iron and steel materials because of both the degree of complexity and volume of information which would be required. Presentation is limited to general thermal conductivity and specific heat charts applicable to most common structural materials and a more detailed presentation of plain carbon steel characteristics illustrating the types of deviations anticipated.

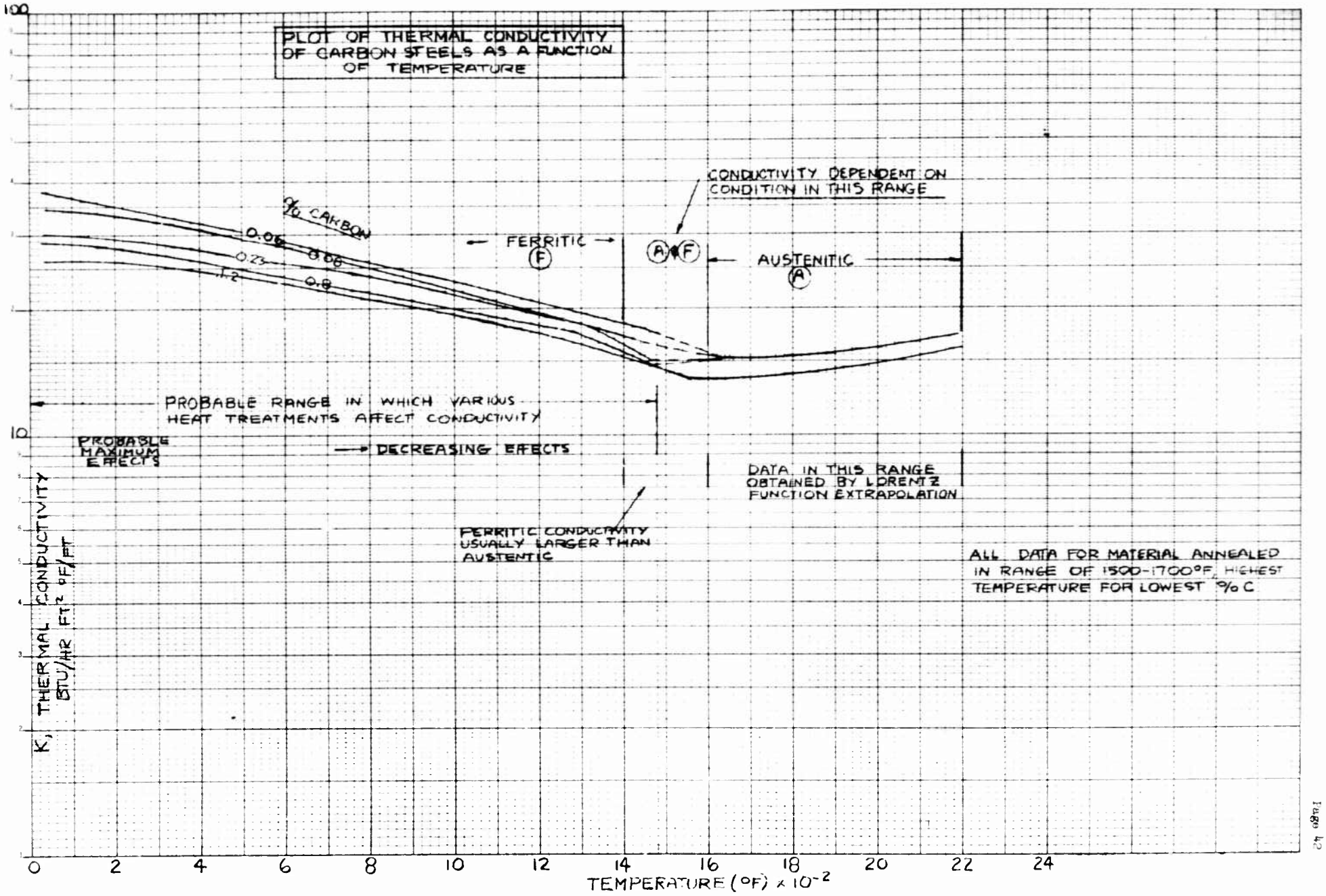
Detailed evaluations of specific materials as regards density, conductivity, specific heat and thermal expansion are available in the following references, and in standard texts.

REFERENCES

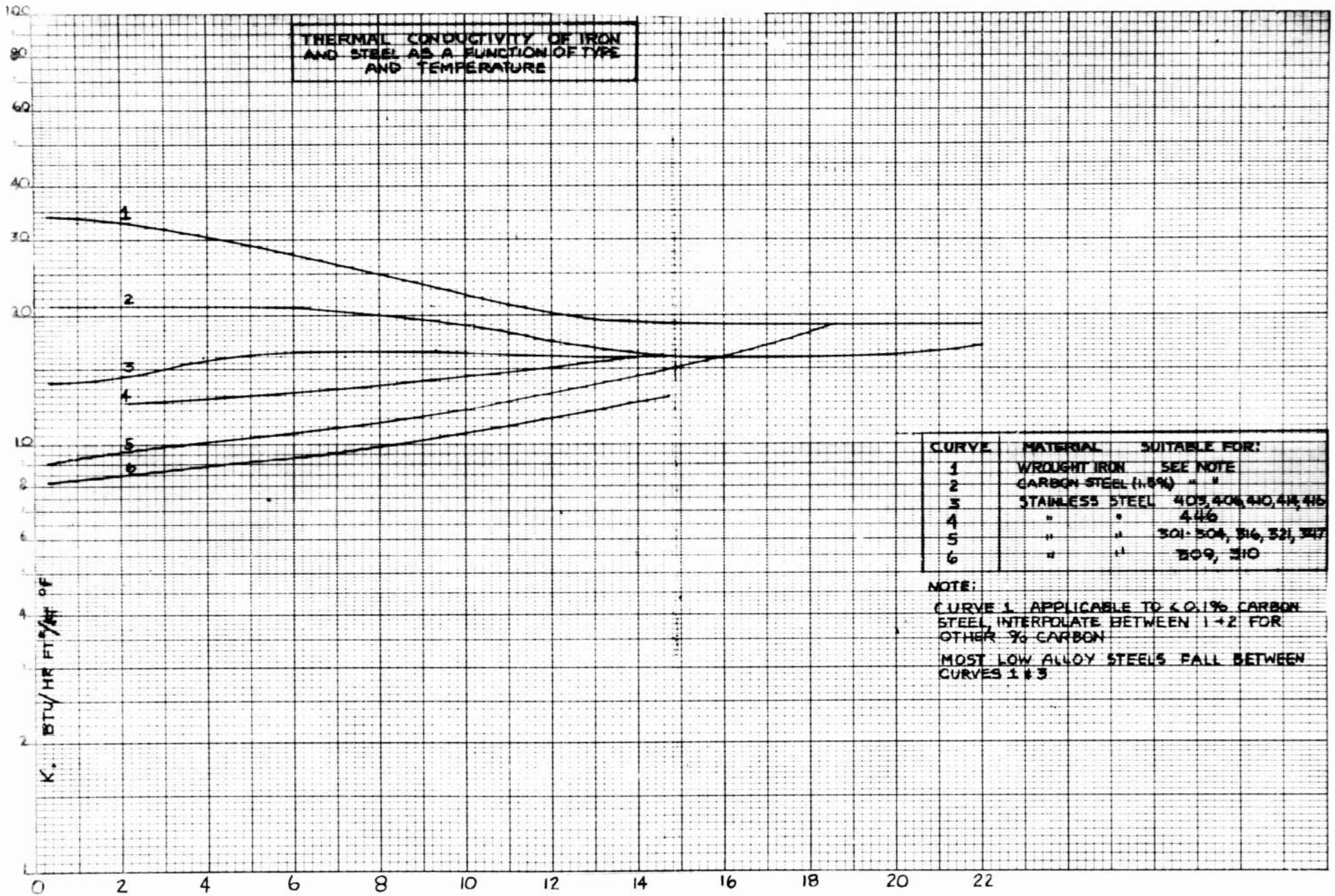
1. Brit. Iron and Steel Research Assoc., "Physical Constants of Some Commercial Steels at Elevated Temperature", Butterworths Scientific Publications London (1953) (Density, Specific Heat, Conductivity, Thermal Expansion).

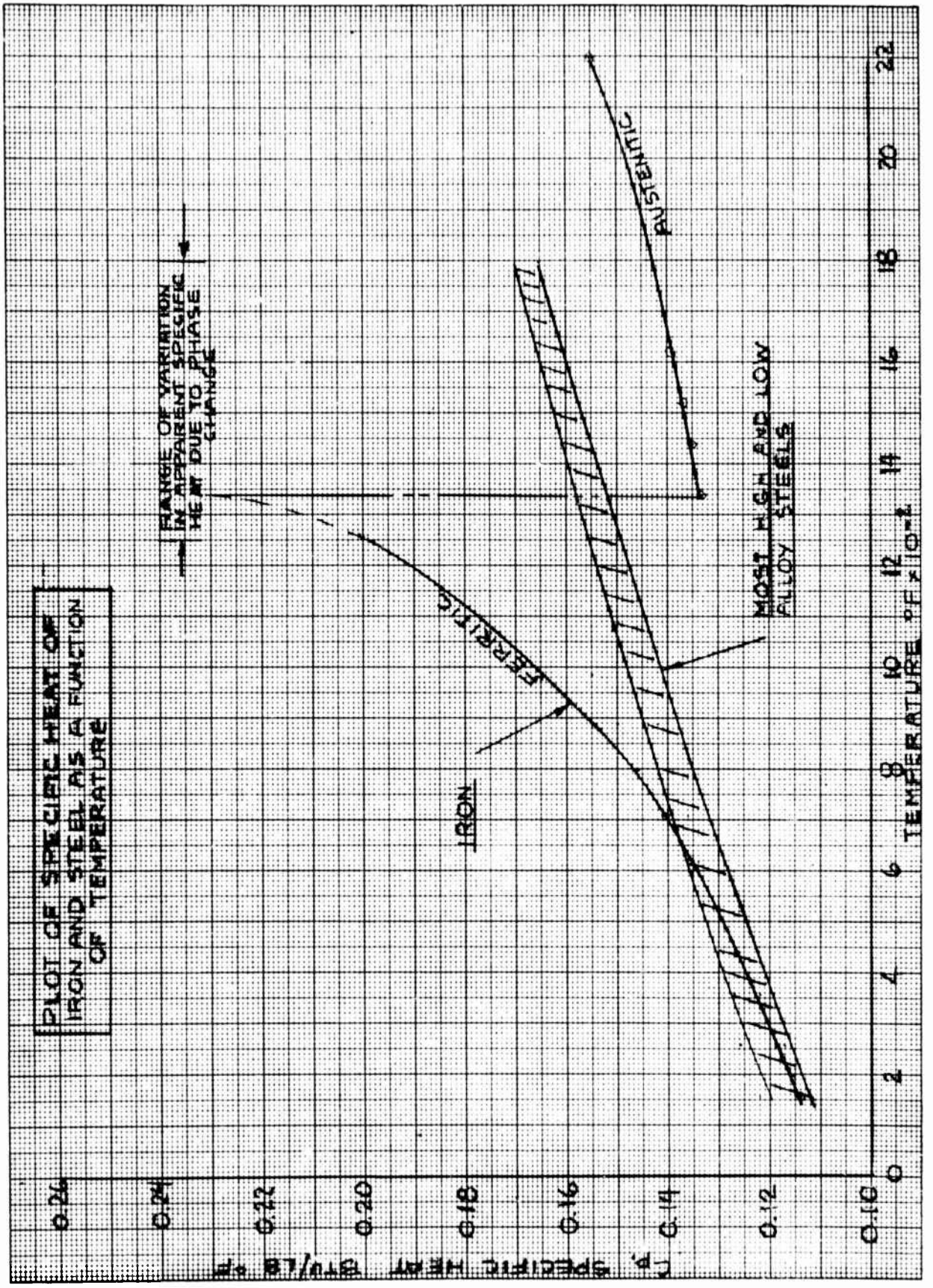
2. Seibel, R. D., Watertown Arsenal Laboratory Report, WAL-821/9 Aug. 1954 (Thermal conductivity).

3. Smithells, C. J., Metals Reference Book, Interscience Publishers, N. Y. (1955) (General).


PLOT OF THERMAL CONDUCTIVITY OF CARBON STEELS AS A FUNCTION OF TEMPERATURE
% CARBON
0.05
0.06
0.23
1.2
0.8
CONDUCTIVITY DEPENDENT ON CONDITION IN THIS RANGE
FERRITIC
(F)
(A) (F)
AUSTENITIC
(A)
PROBABLE RANGE IN WHICH VARIOUS HEAT TREATMENTS AFFECT CONDUCTIVITY
PROBABLE MAXIMUM EFFECTS
DECREASING EFFECTS
DATA IN THIS RANGE OBTAINED BY LORENTZ FUNCTION EXTRAPOLATION
FERRITIC CONDUCTIVITY USUALLY LARGER THAN AUSTENTIC
ALL DATA FOR MATERIAL ANNEALED IN RANGE OF 1500-1700°F, HIGHEST TEMPERATURE FOR LOWEST % C
K, THERMAL CONDUCTIVITY BTU/HR FT² °F/FT
100
10
1
0
2
4
6
8
10
12
14
16
18
20
22
24
TEMPERATURE (°F) x 10⁻²

Page 42


THERMAL CONDUCTIVITY OF IRON AND STEEL AS A FUNCTION OF TYPE AND TEMPERATURE
K, BTU/HR FT²/FT °F
100
80
60
40
30
20
15
10
8
6
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
1
2
3
4
5
6
CURVE | MATERIAL | SUITABLE FOR:
1 | WROUGHT IRON | SEE NOTE
2 | CARBON STEEL (1.5%) | " "
3 | STAINLESS STEEL | 405, 409, 410, 418, 416
4 | " " | 446
5 | " " | 301-304, 316, 321, 347
6 | " " | 309, 310
NOTE:
CURVE 1 APPLICABLE TO < 0.1% CARBON STEEL, INTERPOLATE BETWEEN 1 + 2 FOR OTHER % CARBON
MOST LOW ALLOY STEELS FALL BETWEEN CURVES 1 & 3


PLOT OF SPECIFIC HEAT OF IRON AND STEEL AS A FUNCTION OF TEMPERATURE
RANGE OF VARIATION IN APPARENT SPECIFIC HEAT DUE TO PHASE CHANGE
AUSTENITIC
FERRITIC
IRON
MOST HIGH AND LOW ALLOY STEELS
SPECIFIC HEAT C_p BTU/LB °F
TEMPERATURE °F x 10⁻²
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0
2
4
6
8
10
12
14
16
18
20
22

LEAD

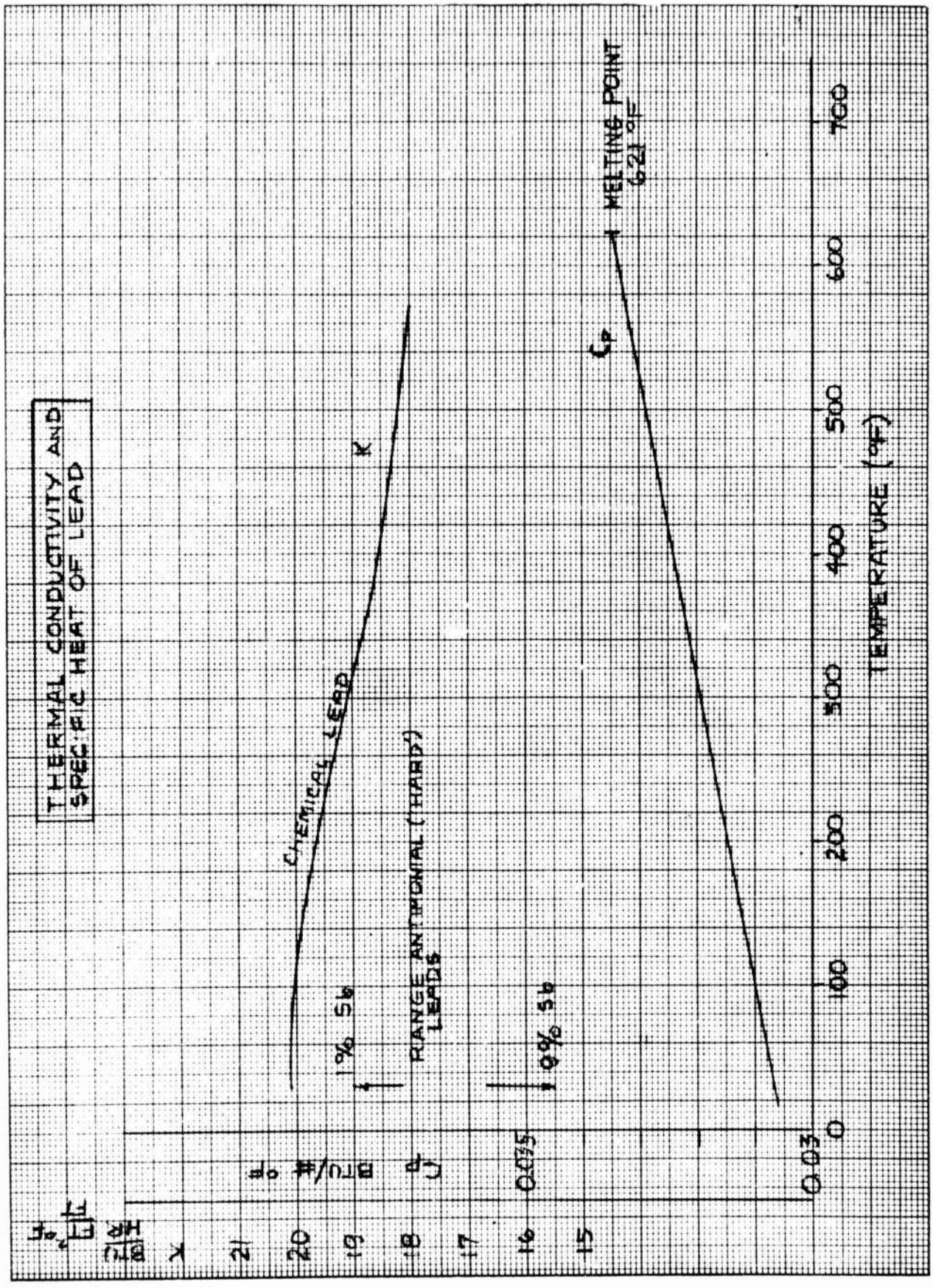
Intensive evaluation of the properties of lead was not attempted because of limitations of material application to Project work and good agreement noted among data of various authors*.

Thermal conductivity data for lead were taken from secondary references including the International Critical Tables, Metals Handbook and National Bureau of Standards Circular 556. Specific heat data were taken from the compilation of Kelley.

Typical values of other properties are as follows:

Density at 70°F	=	0.409 lbs/in^3
Melting Point		620°F
Molecular Weight		207.21
Thermal Expansion		(32 - 212°F) $16.4 \times 10^{-6} \frac{\text{in}}{\text{in}}$ °F

* Lead is often used as the standard in comparative thermal conductivity tests.


THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF LEAD
K
Cp
MELTING POINT 621°F
CHEMICAL LEAD
1% Sb
RANGE ANTIMONIAL ("HARD") LEADS
10% Sb
TEMPERATURE (°F)
0
100
200
300
400
500
600
700
0.03
0.035
15
16
17
18
19
20
21
BTU/# °F
J
K

MOLYBDENUM

Molybdenum metal is available in a variety of densities due to various processes of production and fabrication. Typical density values for various products are as follows:

Powder, bulk density	0.1084 lbs/in^3
Cold-pressed bar	0.2168 "
Sintered bar	0.354 "
Sintered bar worked to wire	0.372 "
Theoretical	0.371 "
Arc Cast	0.368 "

Data presented in this report is primarily concerned with cast or filament density ranges.

Melting Point	4750^c $\pm$ 20^{o}F
Molecular Weight	95.95

Specific Heat

Data presented is the compilation of Kelley (ref. 1).

Linear Coefficient of Expansion

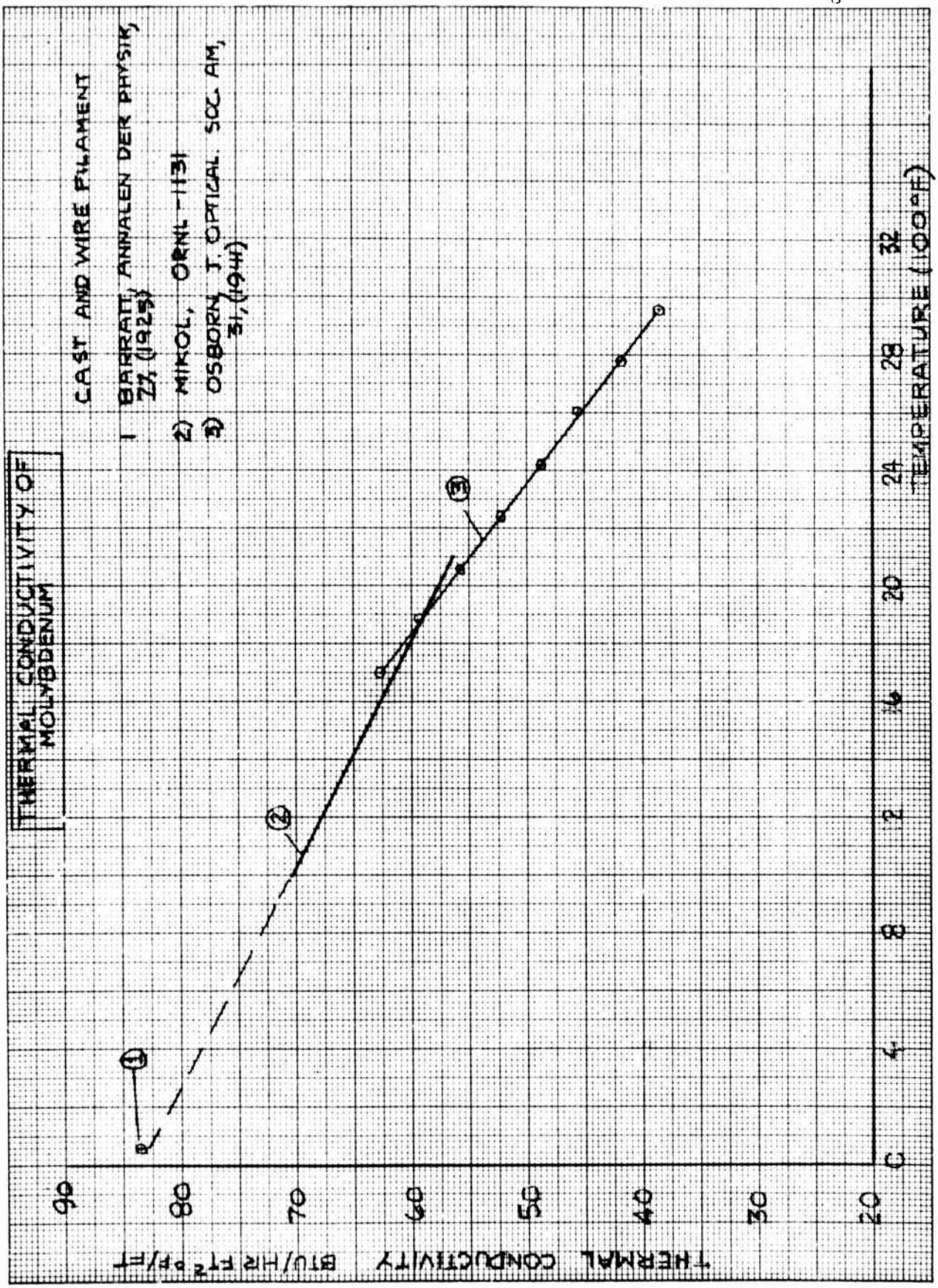
Data presented by various manufacturers and an unclassified compilation in the Reactor Handbook indicate the following values:

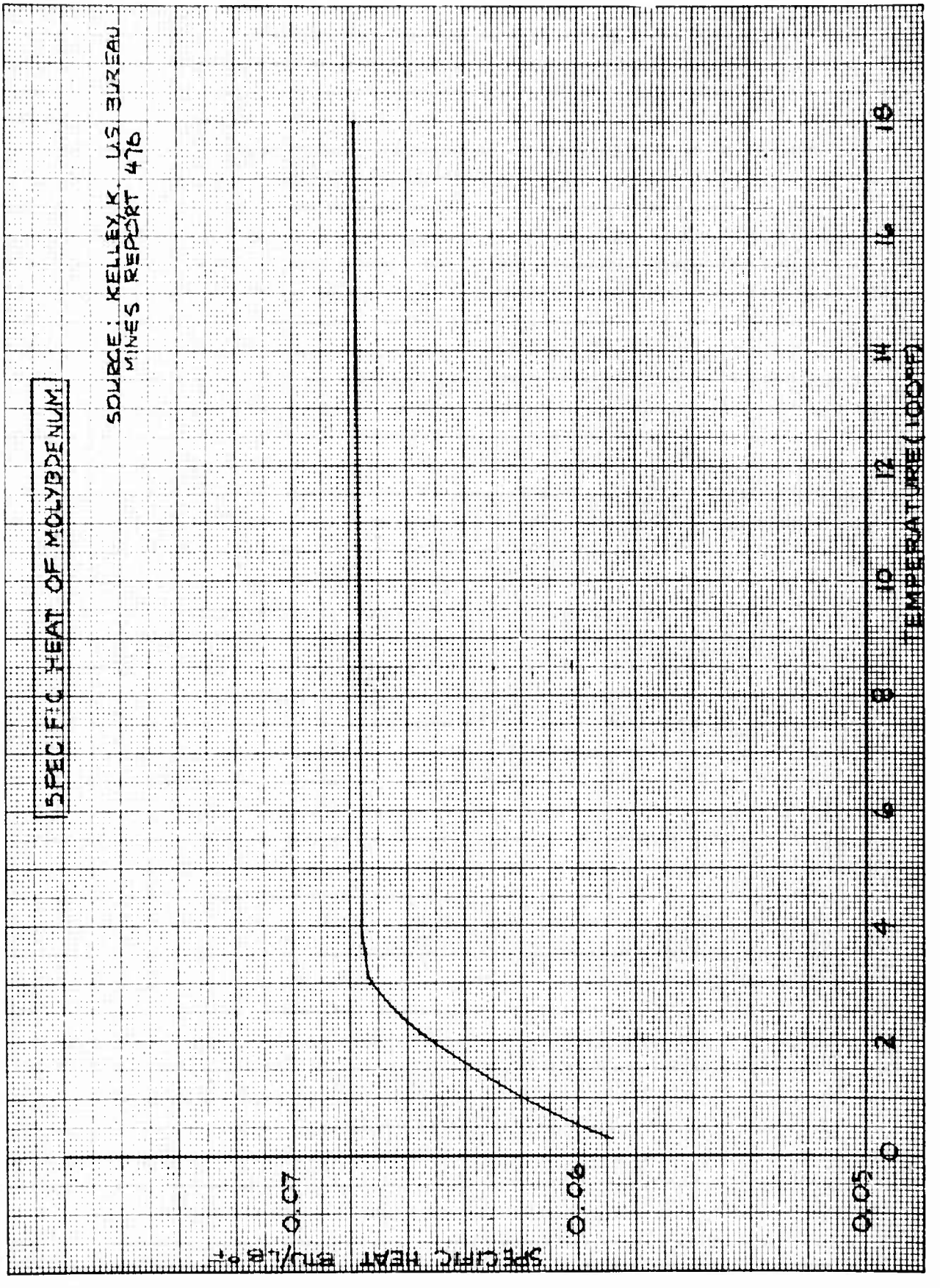
0 - 950^{o}F	2.8 x 10^{-6} in/in ^{o}F
1800^{o}F	3.05 x 10^{-6} "
2700^{o}F	6.2 x 10^{-6} "

Nix reports an average value of 3.16 x 10^{-6} for the range of 0 - 950^{o}F.

Thermal Conductivity

A comparison of the thermal conductivity data reported in three temperature ranges by as many investigators seems to confirm the value of each work.


THERMAL CONDUCTIVITY OF MOLYBDENUM
CAST AND WIRE FILAMENT
1 BARRATT, ANNALEN DER PHYSIK, 77 (1925)
2) MIKOL, ORNL-1131
3) OSBORN, J. OPTICAL SOC. AM, 31, (1941)
THERMAL CONDUCTIVITY BTU/HR FT² °F/FT
TEMPERATURE (1000°F)
90
80
70
60
50
40
30
20
0
4
8
12
16
20
24
28
32


SPECIFIC HEAT OF MOLYBDENUM
SOURCE: KELLEY, K. US BUREAU MINES REPORT 476
SPECIFIC HEAT BTU/LB °F
0.07
0.06
0.05
0
2
4
6
8
10
12
14
16
TEMPERATURE (1000°F)

REFERENCES

1. Kelley, K. K., "Contributions to the Data on Theoretical Metallurgy", U. S. Bureau of Mines Bulletin 476, 1949.

2. Nix, F. C., et. al. "Thermal Expansion of Pure Metals", Phys. Rev. 61 74 1942.

3. Barratt, Annalen Der Physik 77 1925. "Thermal Conductivity of Wires and Rods".

4. Mikol, E. P., "The Thermal Conductivity of Molybdenum over the Temperature Range 1000 - 2100°F", ORNL 1131 (1952) Uncl.

5. Osborn, R. H., "Thermal Conductivities of Tungsten and Molybdenum at Incondescent Temperatures", Jour. Opt. Soc. Am. 31 428 (1941).

NICHROME V

Thermal Conductivity

The results of various investigators are in fairly good agreement. It is not known if the German reference indicated on the graph is original work.

Specific Heat

The specific heat values presented are from two samples tested at the National Bureau of Standards. The definitely observed break at 1100°F may indicate a change in crystalline form.

Miscellaneous Properties

Ref. (1) indicates a specific gravity of 8.36 (0.302 lb/in^3) for an 80 Ni - 20 Cr wrought alloy. The melting point is given as 2550°F and the thermal expansion coefficient (for the range 32 - 212°F) as 7.3×10^{-6} /°F.

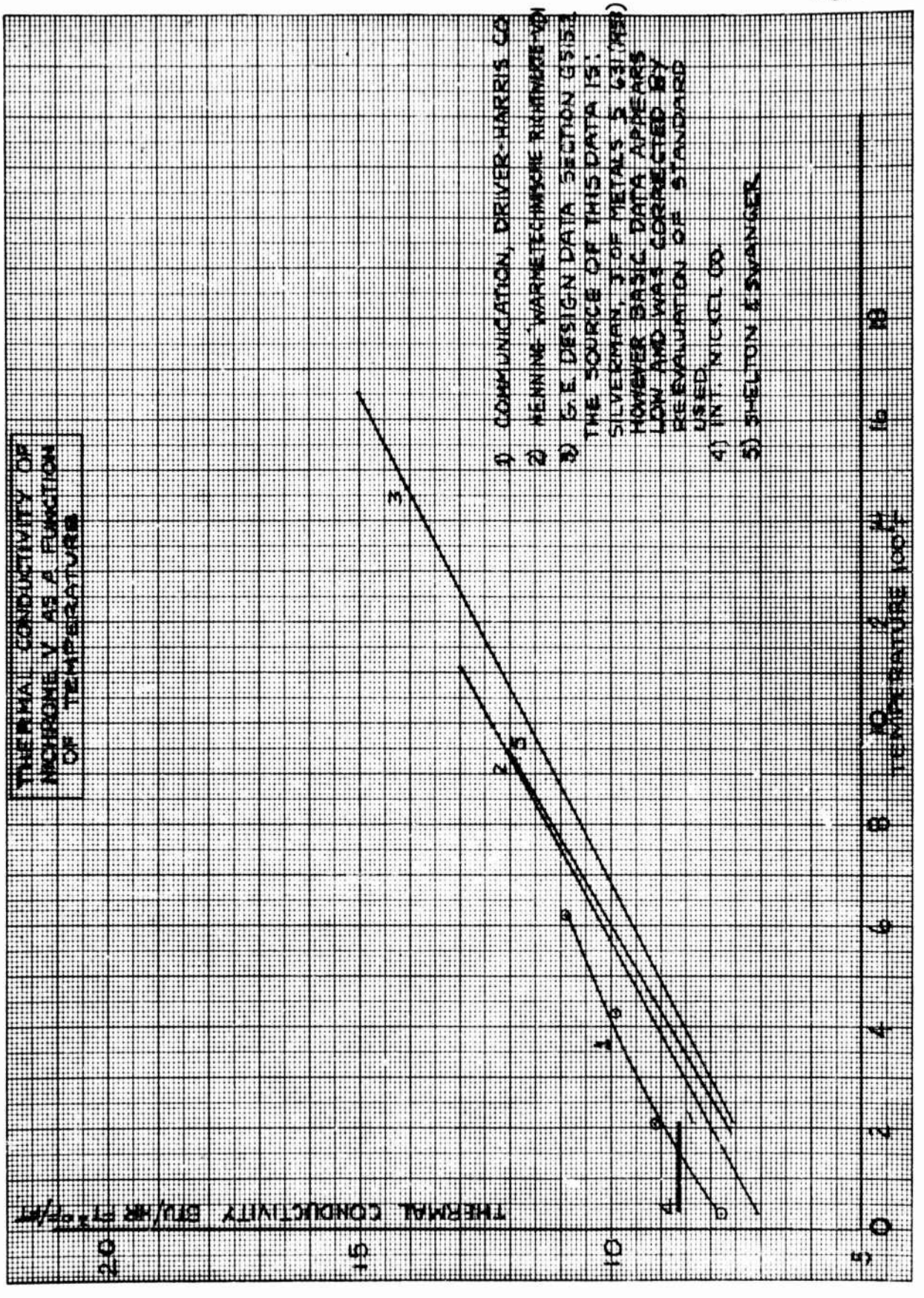
REFERENCES

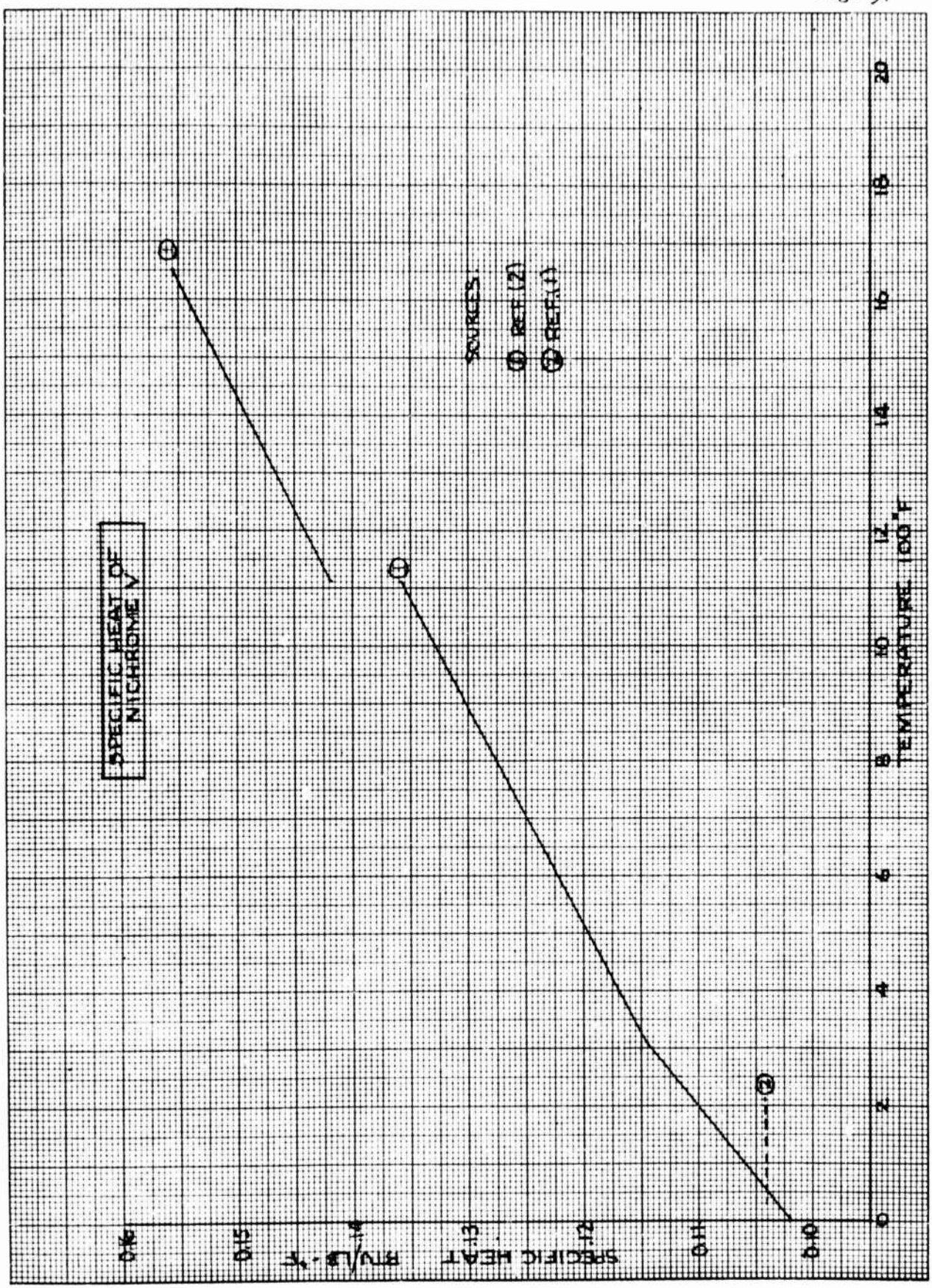
1. "Properties of Some Metals and Alloys", Int. Nickel Co. 1951.

2. Douglas, T. B., and Dever, J. L., "Heat Capacity of Four Alloys, Nichrome V and Stainless Steels Types 347, 446, 0-900°C", Uncl. NBS Report 2302 1953.

3. Silverman, L. "Thermal Conductivity Data Presented for Various Metals and Alloys up to 900°C", Jour. Metal 5 5, 631, 1953.

4. Shelton and Swanger, Trans. Am. Soc. for Steel Treating, 21, 1061, 1933.


THERMAL CONDUCTIVITY OF INCONEL X AS A FUNCTION OF TEMPERATURE
1) COMMUNICATION, DRIVER-HARRIS CO
2) HENNING WARMETECHNISCHE RICHTWERTE (VDI)
3) G.E. DESIGN DATA SECTION G15.1
THE SOURCE OF THIS DATA IS:
SILVERMAN, J. OF METALS 5 631 (1953)
HOWEVER BASIC DATA APPEARS
LOW AND WAS CORRECTED BY
REEVALUATION OF STANDARD
USED.
4) INT. NICKEL CO.
5) SHELTON & SWANGER
THERMAL CONDUCTIVITY BTU/HR FT°F/FT
TEMPERATURE 100°F


SPECIFIC HEAT OF NICHROME V
SOURCES:
① REF.(2)
② REF.(1)
SPECIFIC HEAT BTU/LB - °F
0.10
0.15
0.20
0
2
4
6
8
10
12
14
16
18
20
TEMPERATURE, 100 °F

NIOBIUM
(Columbium)

Miscellaneous Properties

Melting Point	4370°F, (Ref. 1)
Density	8.6 gm/cm^3
Electrical Resistivity	14.1 microhm - cm (32-212°F) (Ref. 2)

Thermal Expansion

The thermal expansion data shown on the curve was obtained (Ref. 3) on a 99.8% pure sample by x-ray methods. The specimen was found to be body-centered cubic in form at room temperature and in the range investigated (1500 - 4000°F). Reference 5 presents the following mean coefficients of expansion for the ranges indicated:

Temp. Range °F	Expansion Coefficient ($°F^{-1}$)
60 - 122	4.0×10^{-6}
60 - 212	4.0 "
60 - 392	4.1 "
60 - 572	4.2 "

This sample contained 1% tin and iron as impurities.

Specific Heat

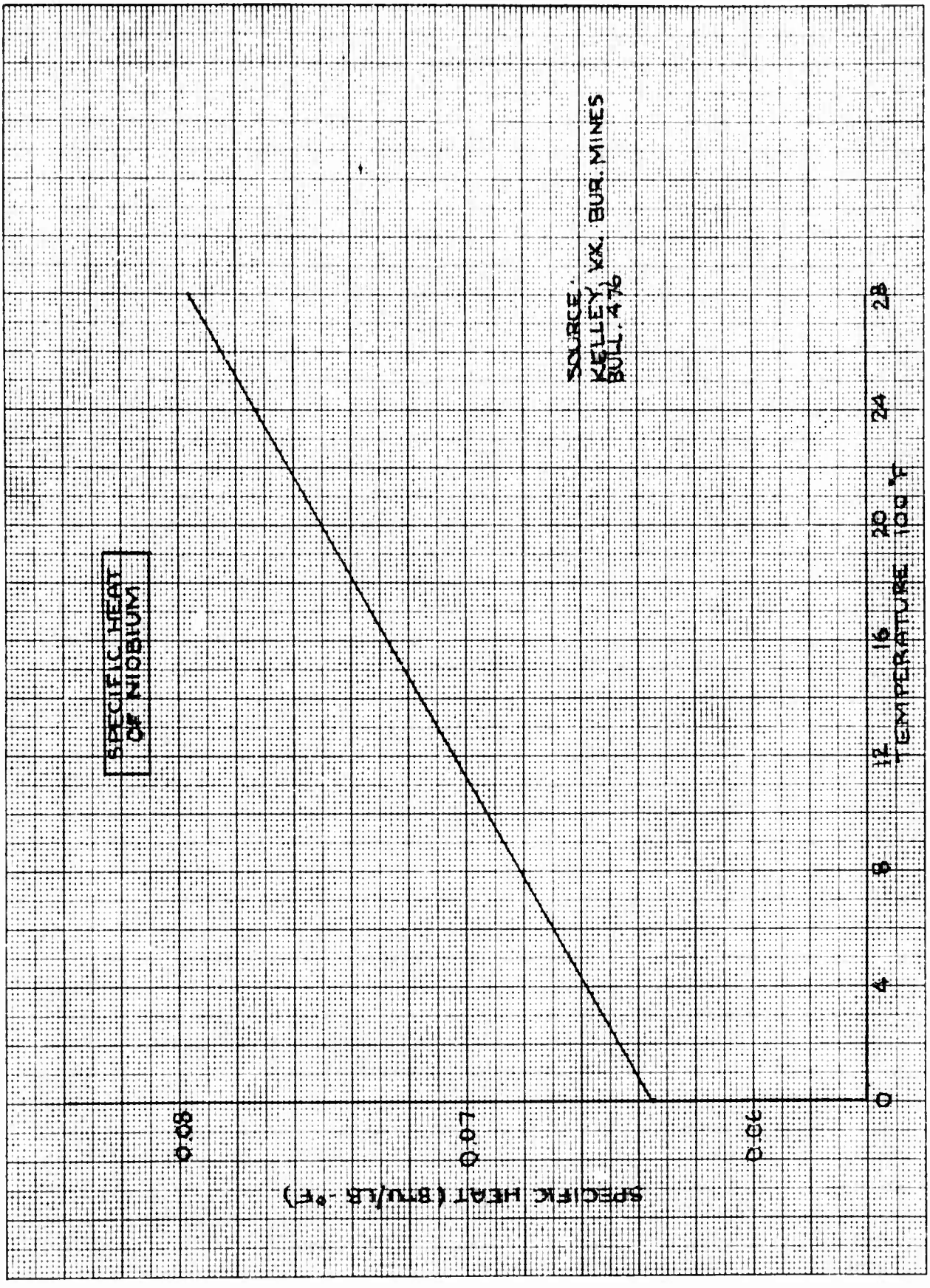
The specific heat data are that of Jaeger and Veenstra as reported by Kelley (Ref. 4) in the form:

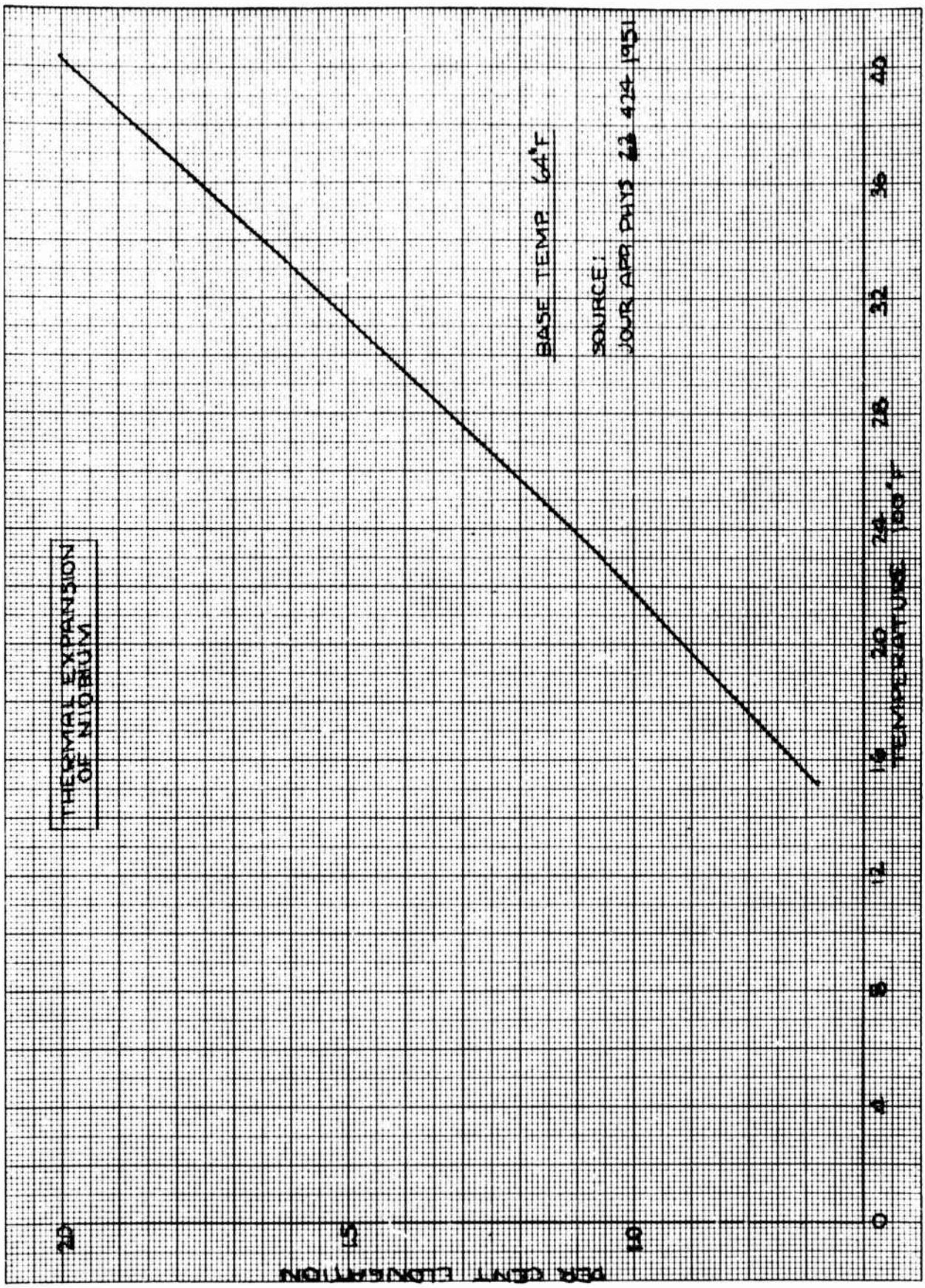
$$C_p = 5.56 + 0.96 \times 10^{-3} T$$

where C_p = cal/°C - mole and T = °K

Thermal Conductivity

The thermal conductivity was estimated with the aid of the Lorenz relation to be about 25 $BTU/ft^2 - °F - Hr/ft$, at room temperature and decreasing to around 20 at 1800°F. The reliability of these estimates cannot be guaranteed. No experimental information concerning conductivity was found in the literature.


SPECIFIC HEAT OF NIOBIUM
SOURCE:
KELLEY, K.K. BUR. MINES
BULL. 476
SPECIFIC HEAT (BTU/LB - °F)
0.08
0.07
0.06
0
4
8
12
16
20
24
28
TEMPERATURE 100 °F


THERMAL EXPANSION OF NIOBIUM
BASE TEMP. 64°F
SOURCE:
JOUR. APP. PHYS. 22 424 1951
PER CENT ELONGATION
TEMPERATURE (100°F)
0
4
8
12
16
20
24
28
32
36
40
5
10
20

REFERENCES

1. Smithells, C. J., Metals Reference Book, Interscience Publishers, 1955.

2. Van Arkel, A. E., "Reine Metalle", Berlin 1939.

3. Edward, J. W. et. al. "High Temperature Structure and Thermal Expansion of Some Metals as Determined by X-ray Diffraction Data. I Platinum, Tantalum Niobium and Molybdenum", Jour. App. Physics 22 4, 424, 1951.

4. Kelley, K. K., "Contributions to the Data on Theoretical Metallurgy", U. S. Bureau of Mines Bulletin 476, 1949.

5. Hidnert, P, and Krider, H. S., NBS Report RP 590, 1933.

URANIUM

In the range of atmospheric temperature to its melting point (2070°F) uranium exists in three different crystalline forms as indicated in the following table.

PHASE

Property	Alpha	Beta	Gamma
Stability Range	To 1224°F	1224 - 1422	1422 - 2070
Crystal Form	Orthorhombic	Tetragonal	Body-Centered Cubic
Density #/in^3	0.686	0.654	0.652
@ Temp °F	68	1330	1480

Variations of continuity of specific heat, coefficient of thermal expansion and thermal conductivity relationships could be expected as a result of the indicated phase changes. Anisotropic effects could also be anticipated due to the low symmetry of the alpha phase structure.

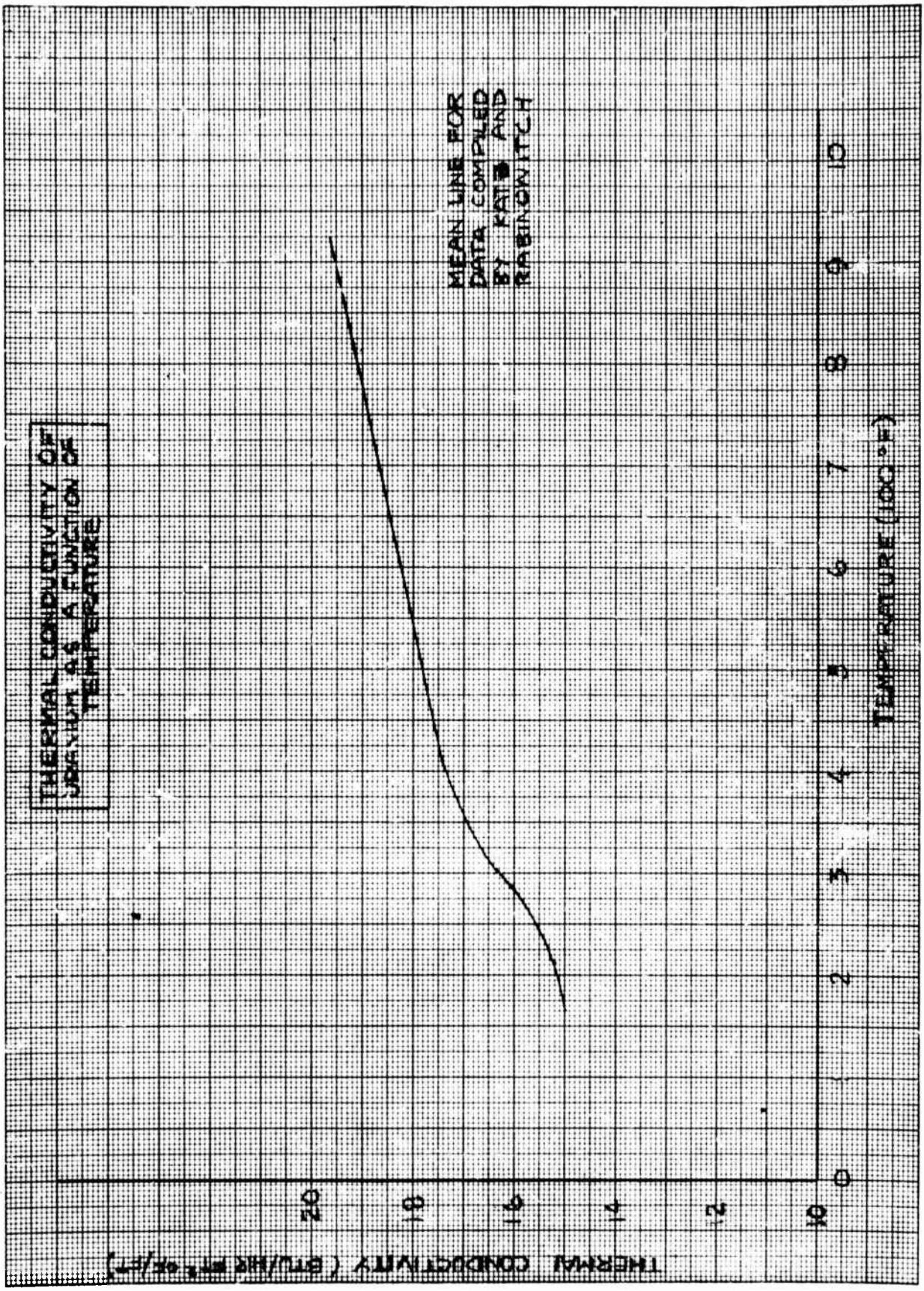
Density values for most available materials are somewhat lower than theoretical values due to inclusion of impurities such as carbon. Typical density for materials are as follows:

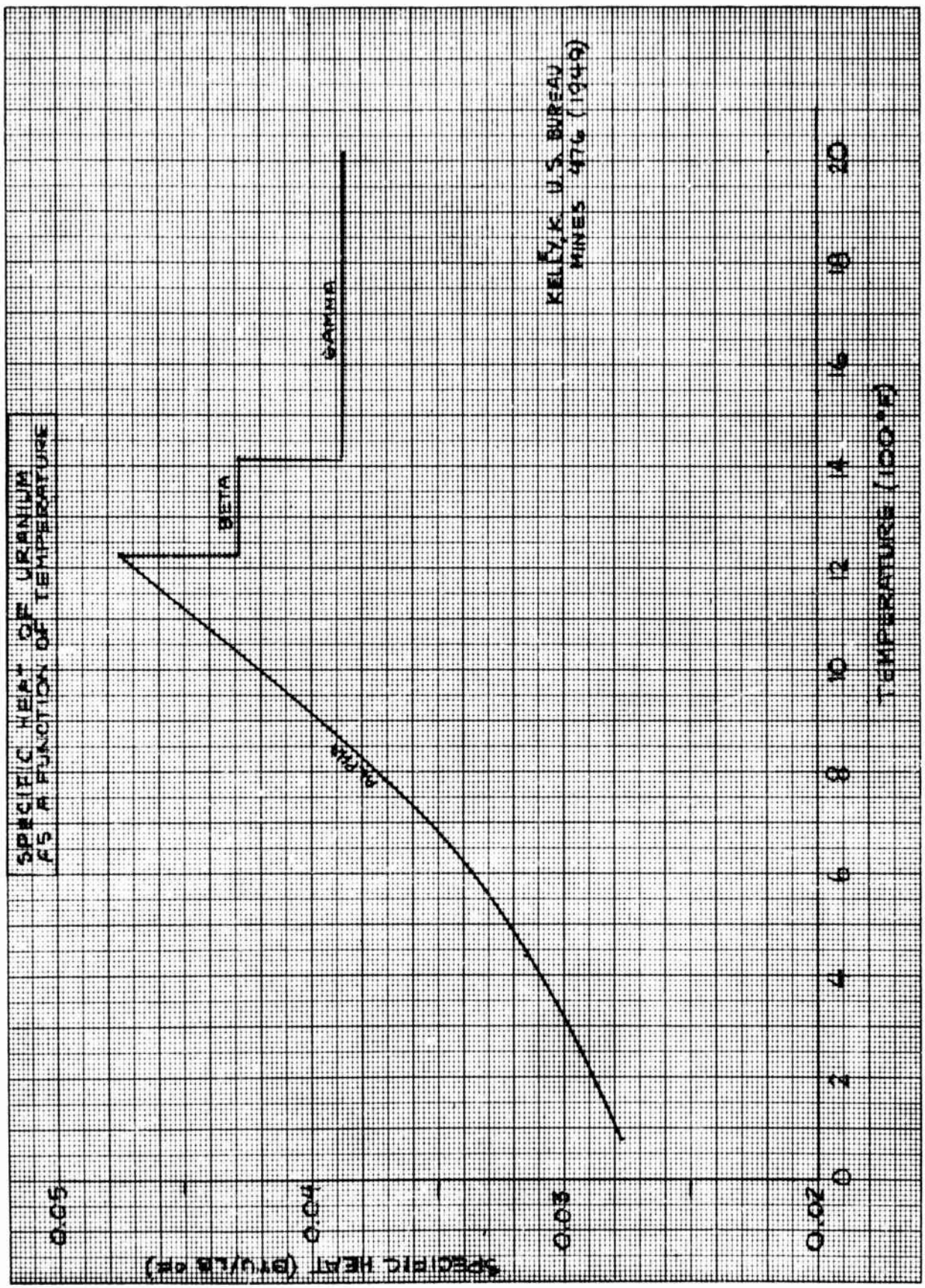
Theoretical density	0.691 #/in^3
Wrought material	0.668 - 0.686
Sintered & Pressed	0.682
Cast (70°F)	0.668

Most data applicable to evaluation of physical properties of uranium as derived from Manhattan Project work are present in detail by Katz and Rabinowitch, together with a tabulation of original references. Since this work is available an extensive bibleography and survey of data is not included in this report.

REFERENCES

1. J. J. Katz & E. Rabinowitch, "The Chemistry of Uranium, NNES, Div. VII, Vol. 5, (McGraw-Hill 1951).


THERMAL CONDUCTIVITY OF URANIUM AS A FUNCTION OF TEMPERATURE
MEAN LINE FOR DATA COMPILED BY KATZ AND RABINOWITCH
THERMAL CONDUCTIVITY (BTU/HR FT °F/FT)
TEMPERATURE (100 °F)
0
2
4
6
8
10
20
18
16
14
12


SPECIFIC HEAT OF URANIUM AS A FUNCTION OF TEMPERATURE
KELLEY, U.S. BUREAU MINES 477 (1949)
ALPHA
BETA
GAMMA
SPECIFIC HEAT (BTU/LB °F)
TEMPERATURE (100 °F)
0.02
0.03
0.04
0.05
0
2
4
6
8
10
12
14
16
18
20

APPENDIX

I. ADDITIONAL DATA

A fairly extensive evaluation of the thermal conductivity of metallic materials for the temperature range of 32 - 1650°F is presented by Silverman (1). HOWEVER THESE DATA APPEAR TO BE INCONSISTENT WITH ALTERNATE DATA FROM OTHER SOURCES AND THEIR USE IS NOT RECOMMENDED. Communication with Mrs. Nancy Fitzroy of General Engineering Laboratories indicates that the deviations noted in Silverman's work are possibly attributable to incorrect evaluation of the standard sample ("Advance") used for comparative analysis. Silverman's data, as quoted in the G. E. Design Data Book, were corrected on this basis by Mrs. Fitzroy; however, data were marked as unreliable.

Check of Silverman's data against information gathered for this report generally indicated that values were low by some 20 - 50%. However, no consistent correction factor could be determined.

The summary of Silverman data is included in this report for purposes of reference, comparison and potential value. Since these data are fairly extensive, it could be anticipated that they will appear in secondary reference sources. It is believed that these data should nevertheless be regarded as erroneous pending further clarification.

THERMAL CONDUCTIVITY OF METALS

Source: Silverman, L., Journal of Metals 5, Section 1, 631 (May 1953)

TABLE I. Chemical Analyses of Materials Tested

Material	Anneal Temp. °C.	Analysis, Pct Percent Ni	Fe	Cu	Cr	Co	Mo	Mn	C	Si	P	S	Mg	Ti
Lohm	900	6.05		93.4				0.01		0.01				
A Nickel	900	Bal	0.26	0.063		0.746	0.705				0.036			
Advance	900	44.04		54.79				1.20	0.035	0.003				
D Nickel	900	92.79	1.35			1.27		4.35	0.158	0.06				
Monel	950	66.2	1.88	30.0		0.407		0.919	0.40	0.135			0.032	
RCA N91	1000	78.1				21.6		0.185	0.115				0.01	
RCA N97	1000	59.5				40.0		0.175	0.132	0.19			0.01	
302 Stainless	1100	9.60	71.60		18.40				0.116	0.130	0.021	0.013		
Nichrome V	950	77.94	0.036		19.87			0.06		1.44				
Hastelloy A	1150	57.1	21.4				19.0	2.5	0.072					
430 Stainless	050		82.4		17.2			0.254	0.102			0.035		
Inconel	1050	78.13	6.33		13.94	0.30		0.32		0.33				
446 Stainless	900		76.44		25.58			0.043	0.152			0.021		
52 Pct Nickel Iron	950	50.85	48.5					0.12	0.024			0.003		
Svea Iron	900		Bal					0.02	0.026	0.28	0.021	0.011		
Kovar	900	28.75	53.7			17.15		0.47	0.017					
42 Pct Nickel Iron	950	43.91	55.8					0.22	0.050			0.003		
Titanium	700		0.04					0.10	0.035				0.01	Bal

TABLE II. Thermal Conductivity of Various Materials, Watts/cm°C

Material	50°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C
Lohm	0.889	0.907	0.944	0.980	1.016	1.053	1.089	1.126	1.162	1.199
A Nickel	0.610	0.582	0.525	0.470	0.446	0.447	0.509	0.540	0.587	0.604
Advance	0.194	0.212	0.251	0.289	0.328	0.367	0.405	0.463	0.481	0.520
D Nickel	0.430	0.403	0.350	0.300	0.334	0.367	0.399	0.431	0.464	0.497
Monel	0.173	0.189	0.222	0.255	0.288	0.321	0.355	0.388	0.422	0.455
RCA N91	0.446	0.437	0.419	0.401	0.383	0.366	0.359	0.380	0.401	0.421
RCA N97	0.418	0.411	0.398	0.384	0.370	0.356	0.343	0.339	0.315	0.301
302 Stainless	0.123	0.133	0.151	0.168	0.186	0.204	0.221	0.239	0.256	0.274
Nichrome V	0.103	0.112	0.130	0.148	0.166	0.183	0.201	0.220	0.238	0.255
Hastelloy A	0.105	0.114	0.131	0.148	0.166	0.183	0.201	0.218	0.236	0.253
430 Stainless	0.220	0.222	0.226	0.229	0.233	0.237	0.240	0.244	0.248	0.252
Inconel	0.111	0.119	0.136	0.152	0.169	0.185	0.202	0.218	0.235	0.251
446 Stainless	0.176	0.180	0.186	0.192	0.198	0.204	0.210	0.216	0.222	0.228
52 pct Nickel Iron	0.181	0.183	0.189	0.194	0.199	0.204	0.209	0.214	0.219	0.224
Svea Iron	0.690	0.662	0.606	0.552	0.494	0.438	0.384	0.330	0.274	0.220
Kovar	0.142	0.147	0.150	0.156	0.166	0.175	0.184	0.193	0.201	0.210
42 pct Nickel Iron	0.159	0.161	0.165	0.169	0.171	0.174	0.178	0.181	0.184	0.188
Titanium	0.154	0.152	0.148	0.144	0.140	0.137	0.133	0.129		

II. EQUIVALENT UNITS FOR THERMAL CONDUCTIVITY

Btu / hr-ft^2-$^\circ$F/ft	gm-cal / sec-cm^2-$^\circ$C/cm	watts / cm^2-$^\circ$C/cm	kg-cal / hr-m^2-$^\circ$C/m
1	0.004134	0.01731	1.488
241.9	1	4.187	360
57.79	0.2388	1	86
0.672	0.002778	0.01163	1